# CHAPTER 6

# HIGHWAY INFRASTRUCTURE

## INTRODUCTION

Highway infrastructure protection has been an important consideration in determining the parameters of truck size and weight (TS&W) limits. Pavement wear increases with axle weight; the number of axle loadings; and the spacing within axle groups, such as a tandem or tridem groups. Truck weight also affects the design and fatigue life of bridges. As with pavements, the distribution of weight over the distance between truck axles also affects bridge design and fatigue life. Truck dimensions influence roadway design and vice versa: truck width affects lane widths, trailer or load height affects bridge and other overhead clearances, and length affects the degree of curvature and intersection design. Looking at truck design as determined by the existing roadway geometry, the reverse of the preceding points are true.

Alternative vehicle configurations, analyzed in terms of their interaction with highway infrastructure features include single-unit or straight trucks and single- and multi-trailer truck combinations. Pavement types analyzed include flexible, asphaltic concrete, and rigid, portland cement concrete. Bridge features included in the analysis are span length and clearances. The list of roadway geometry features analyzed is extensive and includes interchange ramps, intersections, and climbing lanes.

## INFRASTRUCTURE IMPACTS OVERVIEW

TS&W characteristics--axle weights, gross vehicle weight (GVW), truck length, width, and height--impact of pavements, bridges, and roadway geometry in different ways as shown in Table VI-1.

**TABLE VI-1**
**HIGHWAY INFRASTRUCTURE ELEMENTS AFFECTED BY TS&W LIMITS**

| Highway Infrastructure Element | | Axle Weight | Gross Vehicle Weight | Truck Length | Truck Width | Truck Height |
|---|---|---|---|---|---|---|
| **Pavement** | Flexible | E | | | | |
| | Rigid | E | | | | |
| **Bridge Features** | Short Span | E | | E | | |
| | Long Span | | E | E | | |
| | Clearance | | | | e | E |
| **Roadway Geometric Features** | Interchange Ramps | | e | E | e | |
| | Intersections | | | E | e | |
| | Climbing Lanes | | E | | | |
| | Horizontal Curvature | | e | e | | |
| | Vertical Curve Length | | E | | | |
| | Intersection Clearance Time | | E | E | | |
| | Passing Sight Distance | | | e | | |

Key: E Significant effect
e Some effect

## IMPACT OF WEIGHT

The relationship of weight to overall condition and performance of the highway system is indicated for each infrastructure element presented in Table VI-1: bridges, pavements, and roadway geometry. There are two aspects of weight that are dependent on each other and interact with the highway infrastructure, axle weight (loading) and GVW. As shown in Table VI-1, the effect of axle weight is more significant to pavements and short span bridges, whereas the GVW is of more significance to long span bridges.

Generally, highway pavements are stressed by axle and axle group loads directly in contact with the pavement rather than by GVW. The GVW, taking into account the number and types of axles and the spacing between axles, determines the axle loads. Over time, the accumulated strains (the pavement deformation from all the axle loads) deteriorate the pavement condition, eventually resulting in cracking of both rigid and flexible pavements, and permanent deformation or rutting in flexible pavements. Eventually, if the pavement is not routinely maintained, the axle loads, in combination with environmental effects, accelerate the cracking and deformation. Proper design of pavement relative to loading is a significant factor, and varies by highway system.

Axle groups, such as tandems or tridems, distribute the load along the pavement allowing greater weights to be carried, resulting in the same or less pavement distress than that occasioned by a single axle at a lower weight. The spread between two consecutive axles also affects pavement life or performance; the greater the spread the more each axle in a group acts as a single axle. For example, a spread of nine to ten feet results in no apparent interaction of one axle with another, and each axle is considered a separate loading for pavement impact analysis or design purposes. Conversely, the closer the axles in a group are, the greater the weight they may carry without increasing pavement wear beyond that occasioned by a single axle, dependent on the number of axles in the group. The benefit to pavements of adding axles to a group decreases rapidly beyond four axles.

Axle loads also have an effect on short span bridges, that is, bridge spans that are shorter than the wheelbase of the truck. This results in only one axle group, the front or rear axle group, being on the span at one time. In contrast to pavement impacts, spreading the axles in an axle group is beneficial to short span bridges.

As noted, it is not GVW but rather the distribution of the GVW over axles that impacts pavements. However, GVW is a factor for long span bridges, that is, bridge spans that are longer than the wheelbase of the truck. Bridge bending stress is more sensitive to the spread of axles than to the number of axles. Bridge Formula B takes into account both the number of axles and axle spreads in determining the GVW allowed.

In the context of roadway geometrics, increasing the GVW affects a truck's ability to accelerate from a stop, to enter a freeway, or to maintain speed on a long grade. Acceleration from a stop influences the time required to clear an intersection. Acceleration into a freeway affects the determination of acceleration lane length requirements. Inability to maintain speed on a long grade results in required construction of truck climbing lanes. Some of these effects can be ameliorated by changes in truck design, primarily engine and drive train components. GVW also has a second order effect on off-tracking. “Offtracking” refers to how the rear axle of a trailer tracks relative to the steering axle of the truck. Other truck characteristics that are impacted by roadway geometrics are discussed in more detail later in this chapter.

## IMPACT OF DIMENSIONS

The dimensions of trucks and truck combinations have varied effects on the three elements of highway infrastructure. The most significant effects relate to length, particularly when combined with GVW. Width has a limited effect on swept path, the combination of off-tracking and vehicle width. The effect for highway geometrics of swept path is on ramp or intersection design which is based on mapping a maximum swept path that the truck encroaches on the shoulder, over the curb, or into another lane of traffic. Height regulations are intended to ensure trucks will clear overhead bridges, bridge members, overhead wires, traffic signals and other obstructions.

In general, truck length, or more specifically wheelbase, has a strong effect on bridge bending stress for long span bridges.[1] A truck at mid-span is the loading condition for the maximum bending moment (stress) in a simple supported span. This is not the case for some continuous supported spans. When a truck is straddling the center pier of a continuous span, increasing the truck length can increase the bending moment in the span at the pier.

The effect of truck wheelbase on off-tracking is reduced considerably if the combination is articulated, especially in a multi-trailer combination. Low-speed off-tracking affects interchange and intersection design and high-speed off-tracking affects lane width.

# BRIDGE IMPACTS

## BRIDGE DESIGN[2]

Most highway bridges in the United States were designed according to the design manual guidelines of AASHTO. The AASHTO bridge specifications provide traffic-related loadings to be used in the development and testing of bridge designs, as well as other detailed requirements for bridge design and construction.

Dynamic effects can also be important, particularly for bridges carrying trucks operating at higher speeds. In bridge design, the static weight of design loadings are adjusted upward to

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1 The longer the wheelbase the shorter the distance from the support member to where the load is being applied (the moment arm) when the truck is in the middle of the span. The shorter the truck the greater the concentration of load at the middle of the span, and the longer the distance (moment arm) to the support member for the bridge span member.

2 A substantial amount of the background material is drawn from the TRB Special Report 225, *Truck Weight Limits: Issues and Options*, 1990 and from the 1981 U.S. DOT Report to Congress under Section 161, *An Investigation of Truck Size and Weight Limits.*

account for dynamic effects. To minimize the dynamic effects of extra-heavy nondivisible loads on some bridges, permits often require the truck to cross at a very slow speed depending on the GVW.

A key task in bridge design is the selection of bridge members that are sufficiently sized to support the various loading combinations that the structure may carry during its service life. These include dead load (the weight of the bridge itself), live load (the weights of vehicles using the bridge), wind, seismic, and thermal forces. The relative importance of these loads is directly related to the type of materials used in construction, anticipated traffic, climate, and environmental conditions. For a short span bridge (for example, span length of 40 feet), about 70 percent of the load-bearing capacity of the main structural members may be required to support the traffic-related live load, with the remaining 30 percent of capacity supporting the weight of the bridge itself. For a long bridge (for example, span length of 1,000 feet), as much as 75 percent of the load-bearing capacity of the main structural members may be required to support the weight of the bridge.

For overstress, the loading event that governs bridge capacity in most instances is a design vehicle placed at the critical location on the bridge. In certain cases, a lane loading simulating the presence of multiple trucks on a bridge is the governing factor. Bridges are also affected by the dynamic impact and lateral distribution of weight of the trucks; dynamic impact is determined by speed and roadway roughness, and the lateral distribution of loads varies with the position of the truck(s) on the bridge and the girder spacing.

Planning for the rare loading event involves taking a design vehicle or lane loading and applying safety factors to accommodate variations in materials, deterioration, illegal loading, load distribution and dynamic loading conditions. This adjustment of the nominal legal loading is reflected in the safety factors, which are selected so that there is only a very small probability that a loading condition that exceeds its load capacity will be reached within the design life of a bridge.

The methods used to calculate stresses in bridges caused by a given loading are necessarily conservative, and therefore the actual measured stresses are generally much less than the calculated stresses. A margin of safety is necessary because:

- *The materials used in construction are not always completely consistent in size, shape,and quality,*
- *The effects of weather and the environment are not always predictable,*
- *Highway users on occasion violate vehicle weight laws,*
- *Legally allowed loads often increase during the design life of a structure, and*
- *Occasional overweight loading by permit.*

Some of the added margins of safety used by bridge engineers in the past have been eroded in recent bridge design and construction.  Use of new design procedures and computer-aided engineering and design has enabled more precise analysis of load effects and the selection of lowest size bridge members and configurations.  The competition between steel and concrete has led each group to foster lower costs for their own material.  For example, many designs now proposed for steel reduce the safety factor by reducing the number of girders which increases their spacing.  Good load models and regulations may need to be considered in the future to cover more load increases.

## BRIDGE IMPACT MEASURES

Past studies of the impact of truck weight limit changes on bridges were based on various percentages of the yield stress for steel girder bridges, including 55 percent, 65 percent, and 75 percent of the yield stress.  The yield stress, a property of the particular type of steel, is the stress at the upper limit of the elastic range for bridge strain.  The elastic range of a structural member is the set of stresses over which the deformation, that is, the strain of the member is not permanent.  In the elastic range the member returns to its former size and shape when the stress is removed.  There is no permanent set in the structural member.  For this discussion, strain is the elongation of a steel girder when: (1) a portion of the strain becomes permanent at a stress level above the yield stress; and (2) the girder continues to elongate, or stretch, under increasing load until it ruptures or fails. Beyond the elastic range, there is permanent elongation of the bridge girder, that is, for those stresses that are greater than the yield stress. However, in structural steel there is considerable strain before failure occurs.  This is relative to the strains (elongations) that occur within the elastic range.

### BRIDGE INVENTORY AND OPERATING RATINGS

States rate bridges, at their discretion, at either the inventory rating  (55 percent of the yield stress), or the operating rating (75 percent of the yield stress)[3].  Of course, bridges are never intentionally loaded to yield stress in order to provide an adequate margin of safety.  The design stress level for bridges is based on an operating rating of 55 percent of yield stress.  These two ratings are also used for posting bridges; either may be used under the American Association of State Highway and Transportation Officials (AASHTO) guidelines, at the option of the State.  A bridge is posted with a sign when it is determined that a vehicle above the specified weight would overstress the bridge.  This weight could be that which stresses the bridge at the 55 percent or 75 percent  level, whichever practice the State chooses to use.  As States have the option to use either rating for posting, both ratings have been used in past studies to assess the bridge impacts for illustrative TS&W scenarios (see Volume III).  This is important as there are significant

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[3] According to the AASHTO *Manual for Maintenance Inspection of Highway Bridges* (1983) an operating rating is defined as RF = 0.75-D/L(1+I) where RF= rating factor arrived at with the equation 0.55R= D + L (1 + I) where R= the limiting stress (often the stress at which steel will undergo permanent deformation, or “yield”), D= stress due to dead load (the effect of gravity on bridge components), L= stress due to live load (vehicles on the bridge), I= an adjustment to the static effect of live loads to account for dynamic effects.  An inventory bridge rating is arrived at by selecting the most highly stressed bridge component and inserting the rating factor (RF) into the  Equation, RF= 0.55R- D/L(1 + I), as a multiplier on the live load of the rating truck.

differences in costs that result from choice of rating. Use of the lower stress level (inventory rating) results in more bridges in need of upgrading and, therefore, more costs associated with an increased weight or decreased length limit.[4]

Following the reviews of TRB *Special Reports 225 and 227* (two studies of TS&W limit changes) the FHWA determined that the stress level most representative of all State bridge posting practices was the inventory rating (55 percent of the yield stress) plus 25 percent, which gives a level of 68.8 percent of yield stress. FHWA used this 68.8 percent of yield to estimate the bridge cost impacts of LCVs. The resulting cost estimate reported by FHWA in May 1991 was much closer to the estimate based on the 75 percent rating, the TRB findings in *Special Reports 225 and 227*.

For this current Study, two new stress levels based on the design loading for the bridge in question were chosen--inventory rating plus 5 percent for the HS-20 loading and the inventory rating plus 30 percent for the H-15 loading. These two bridge stress criteria are the same as used in the current Federal bridge formula. Bridges are not generally in need of replacement when trucks meet the Federal bridge formula, as long as they are properly maintained. Selection of bridge evaluation criteria affects the total number of bridges determined to be deficient and associated costs in the analysis of alternative TS&W scenarios (see CTS&W Study Volume III, forthcoming).

Codes developed by AASHTO specify vehicles to represent a broad range of trucks operating at legal weight limits. An H-15 bridge is designed to allow a two-axle truck with a total GVW of 15 tons (30,000 pounds), distributed with 6,000 pounds on the first axle and 24,000 pounds on the second, and axle spacing of 14 feet. An HS-20 bridge is designed to allow a semitrailer combination with a GVW of 36 tons (72,000 pounds) with 8,000 pounds on the tractor's steering axle and 32,000 pounds each on the tractor drive axle and trailer axle. The HS-20 load has a variable axle spacing of 14 feet to 30 feet from the drive to the trailer axle to better cover worst-case situations for continuous spans.

## BRIDGE STRESS CRITERIA

Bridge stresses caused by vehicles depend on both the GVW and the distances between the axles which act as point loads. Trucks having equal weight but different wheelbases produce different bridge stresses. The shorter the wheelbase the greater the stress. On a simple span bridge the length of a truck relative to the length of bridge span is also important. For relatively short spans (20 feet to 40 feet), all axles of a truck combination will not be on the bridge at the same time. The maximum bending moments determine stresses in the main load-carrying members of simple-span bridges.

[4] The TRB *Special Reports 225, Truck Weight Limits: Issues and Options* and *227, New Trucks for Greater Productivity and Less Road Wear: an Evaluation of the Turner Proposal* estimated the bridge costs of the TS&W changes under study based on the operating rating of 75 percent of yield stress, whereas reviewers of those reports found much higher bridge costs resulting from the use of the inventory rating of 55 percent of yield stress.

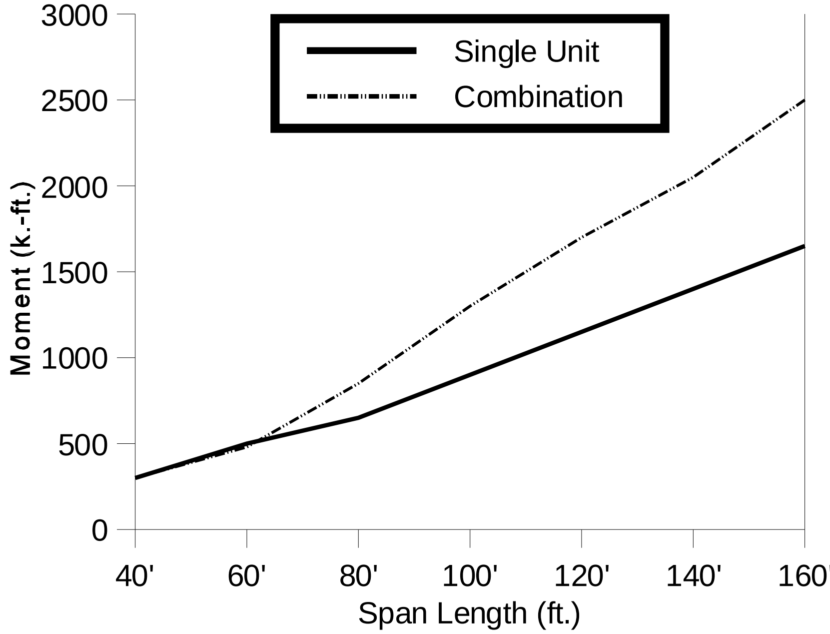
Figure VI-1 shows the maximum bending moments, by span lengths between 40 feet and 160 feet, for two trucks: a 50,000-pound single unit truck with a wheelbase of 19 feet, and an 80,000-pound combination with a wheelbase of 54 feet. For shorter bridges, the 50,000-pound single unit truck produces slightly higher stresses than the 80,000-pound combination; however, for longer bridges the combination produces higher stresses.

Also, estimates of bridge cost impacts of TS&W changes are very sensitive to assumptions regarding acceptable levels of stress on bridges. The inventory rating approach, used by some States, is considerably more conservative than the operating rating approach, used by other States. The inventory rating--equivalent to the design load, which produces a stress of 55 percent of the yield stress--results in no overstress. In comparison, the Federal bridge formula allows up to 5 percent overstresses on HS-20 bridges and 30 percent overstresses on H-15 bridges. The operating rating by allowing 75 percent of yield allows 36 percent more stress than the design load.

## CONSIDERATIONS RELATED TO BRIDGE REGULATION

Only bridge overstress was considered in evaluating the effects of changes in TS&W limits on bridges; fatigue has not been evaluated (see Volume III). Overstress creates the possibility of severe damage and possible collapse caused by a single extreme loading event. Fatigue produces the cumulative damage caused by thousands and even millions of load passages, which can damage some of the more fragile elements of a bridge.

**FIGURE VI-1**
**MAXIMUM BENDING MOMENTS ON A SIMPLE SPAN BRIDGE**
**50,000 pound Straight Truck vs. 80,000 pound Truck Combination**




## OVERSTRESS CRITERIA AND LEVEL OF RISK

The level of risk to accept in determining acceptable loadings for a given bridge, or acceptable bridge design requirements for given loadings, is an element of TS&W regulation. A less conservative bridge formula which did not preserve the underlying Bridge Formula B (BFB) criteria would reduce the margin of safety, thereby increasing somewhat the likelihood of bridge damage due to overstress. An overstress sufficient to damage a bridge would necessitate bridge repair and/or replacement sooner than anticipated.

## BRIDGE FATIGUE

Another factor to be considered is fatigue life which is related to repetitive loadings. Each truck crossing produces one or more stress cycles in bridge components, which use up a portion of the components' fatigue lives. The magnitude of stress depends on vehicle weight and the size of the bridge component. The occurrence of a fatigue failure is signaled by cracks developing at points of high stress concentration.

Generally, only steel bridges are susceptible to fatigue, although some studies suggest that commonly used prestressed concrete spans, if overloaded, are also susceptible to fatigue damage. The governing damage law for steel components has a third-power relationship between stress and damage, so that a doubling of stress causes an eight-fold increase in damage.[5]

Bridge details that are particularly susceptible to fatigue include weld connections in tension zones, pin and hanger assemblies, and cover plates on the bottom flanges of steel beams.[6] Many fatigue failures result from stresses induced indirectly by the distortion of the structure due to poor design details or unforeseen restraints. Most steel cracks reported to date probably fall into the category of distortion induced. Some of the worst detailing can be corrected by repair and retrofit.

## BRIDGE FORMULA B

In addition to axle and maximum GVW limits for Interstate highways, Federal law adopted Bridge Formula B (BFB) that restricts the maximum weight allowed on any group of consecutive axles based on the number of axles in the group and the distance from the first to the last axle.

AASHO proposed the formula concept in the 1940s. It was further developed and presented in a 1964 report to Congress from the Secretary of Commerce. The study[7] recommended a table of maximum weights for axle groups to protect bridges (see Appendix A). The values in the table are derived from the following formula, that is, BFB:

$$W = 500 \left[ L N / ( N - 1 ) + 12 N + 36 \right]$$

*where:*

***W** is the maximum weight* in pounds carried on any group of two or more consecutive axles

***L** is the distance* in feet between the extremes of the axle group

***N** is the number of axles* in the axle group

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5 Fisher, 1977.

6 AASHTO specifications give different allowable fatigue stresses for different categories of detail. These fatigue rules were initiated in the mid-1960s, therefore many older bridges were never checked during their original design for fatigue life. Further, the AASHTO fatigue rules apply to welded and bolted details with stresses induced directly by load passages. (Moses, 1989)

7 *Maximum Desirable Dimensions and Weights of Vehicles Operated on the Federal-Aid System,* 1964 Study Report to Congress, U.S. Department of Commerce.

Federal law specifies exceptions to BFB result given by the above formula: 68,000 pounds may be carried on tandem axles spaced at least 36 feet apart, and a single set of a tandem axle spread no more than 8 feet is limited to 34,000 pounds.

In 1974, Congress adopted BFB, when it increased the GVW limit to 80,000 pounds and the limits on single and tandem axles to 20,000 and 34,000 pounds, respectively. BFB is based on assumptions about the amount by which the design loading can be safely exceeded for different bridge designs. Specifically, this formula was designed to avoid overstressing HS-20 bridges by more than 5 percent and H-15 bridges by more than 30 percent.

The FHWA established a bridge stress level of not more than 5 percent over the design stress for HS-20 bridges to preserve the significantly large investment in HS-20 bridges by Federal, State, and local governments, and because these bridges carry high volumes of truck traffic. Although a level of up to 30 percent is considered to be a safe level for overstressing an H-15 bridge in good condition, the fatigue lives of these structures may be shortened by repeated loadings at this level.

BFB reflects the fact that increasing the spacing between axles generally results in less concentrated loadings and lower stresses in bridge members. For example, the bridge formula would allow a three-axle truck with a wheelbase of 20 feet to operate at 51,000 pounds. If the wheelbase of this truck is increased to 24 feet, then the maximum weight allowed under BFB would increase to 54,000 pounds.

BFB also allows more weight to be carried as the number of axles is increased. For example, if a fourth axle is added to a three-axle truck with a wheelbase of 20 feet, the maximum weight allowed under BFB is increased from 51,000 pounds to 55,500 pounds. Increasing the number of axles in an axle group without increasing the overall length of the group has very little benefit to reducing stress for bridges. However, more axles do provide substantial benefits to pavements.

## POTENTIAL ALTERNATIVES TO BRIDGE FORMULA B

BFB is not just one formula but rather a series of formulas with the appropriate one chosen by a parameter, N, the number of axles in the group in question. However, bridge stress is affected more by the total amount of load than with the number of axles. Thus BFB is not effective in modeling the actual physical phenomenon and results in loads that overstress bridges by more than intended. More importantly, it encourages the addition of axles to obtain more payload even though one or both the bridge stress criteria are exceeded. At other times it inhibits the attainment of legitimate stress levels by the mathematical construct of the controlling equation. In summary, BFB actually results in overstressing some of the bridges it is intended to protect. BFB is not true to its own criteria.

Over the years, there have been a number of proposals to revise the Federal bridge formula. However, significant areas of concern have been identified with respect to the alternatives as well. The following discussion elaborates on three alternatives that have been proposed in recent years:

## TRANSPORTATION RESEARCH BOARD ALTERNATIVE

In 1990, the Transportation Research Board (TRB)[8] recommended adoption of the formula developed by Texas Transportation Institute (TTI) that would allow a 5 percent overstress for HS-20 bridges, in conjunction with existing Federal axle limits for vehicles with GVWs of 80,000 pounds or less. The TRB report further recommended that the BFB continue to be applied to vehicles weighing more than 80,000 pounds. The effect of this proposal would be an increase in maximum weights allowed for shorter vehicles, while the maximum weight limits for the longer wheelbase trucks would remain unchanged. It was asserted that the TTI formula was overly conservative at heavier weights.

The TTI formula is in the form of two equations for straight lines that meet at a wheelbase length of 56 feet. For wheelbases less than 56 feet, it is:

$$W = 1{,}000(L + 34)$$

For wheelbases equal to or greater than 56 feet, it is:

$$W = 1{,}000(L + 62)$$

where: W = allowable weight
L = wheel base for the truck configuration.

## AMERICAN ASSOCIATION OF STATE HIGHWAY & TRANSPORTATION OFFICIALS ALTERNATIVE

In 1993, AASHTO issued a report which recommended that its member committees: (1) evaluate Nationwide adoption of the TTI bridge formula as a replacement for Bridge Formula B; (2) consider a limit on maximum extreme axle spacing of 73 feet in the short-term; (3) retain the existing single- and tandem-axle limits; (4) control tridem axle weights, and the special permitting

[8] 1990 TRB *Special Report 225, Truck Weight Limits: Issues and Options.*

of vehicles with GVWs more than 80,000 pounds, with the original TTI Bridge Formula[9] which protects both H-15 and HS-20 bridges, as opposed to the TTI formula mentioned above, which protects only HS-20 bridges.

## GHOSN ALTERNATIVE

In 1995 a research study for FHWA by Michael Ghosn et al.[10], City College of the City University of New York was published proposing a new formula based on structural reliability theory as a replacement for BFB. Structural reliability theory more explicitly accounts for the uncertainties associated with bridge design and load evaluation. The proposed formula, however is considerably more permissive than BFB, when applied to long vehicles. The proposed formula results in bridge stresses that are well above the criteria selected for this Study. Therefore, it was not considered.

## DIRECT COMPUTATION OF ALLOWABLE WEIGHTS BASED ON BFB STRESS CRITERIA

Original research conducted for this Study suggests that a series of look-up tables may be developed that are based on the underlying stress criteria for BFB, that is: a maximum overstress of 5 percent for HS-20 bridges, and 30 percent for H-15 bridges. These stresses were computed for both simple and continuous spans for the most critical span lengths for the truck configuration. The BFB and TTI formulas are based only on simple spans. As a consequence, some continuous span bridges are stressed beyond the stress criteria on which the Federal and TTI formulas are based.

The look-up tables are generated through application of user friendly computer programs. The following discussion illustrates how this approach might be applied to three vehicles: (1) a tractor-semitrailer combination vehicle with a three-axle tractor and two-axle semitrailer; (2) a tractor-semitrailer combination vehicle with a three-axle tractor and a semitrailer with a tridem-axle group; and (3) a Rocky Mountain Double (RMD).

Illustrative Table VI-2 presents the weight values for the five-axle tractor-semitrailer with a three-axle tractor and two-axle semitrailer under the BFB, TTI and BFB Stress Criteria and Figure VI-2 graphically displays the maximum GVW.

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9 The recommendation was reviewed by the AASHTO Highway Subcommittees on Bridges and Structures and Highway Transport, accepted in resolution form and approved by the Standing Committee on Highways. The AASHTO Board of Directors considered the recommendations at its 1996 Fall meeting. The Board expressed concern that the impact on pavements was not adequately addressed and remanded it for further consideration to the Subcommittees on Design and on Bridges and Structures. It is anticipated the Board will reconsider the recommendations in 1997.

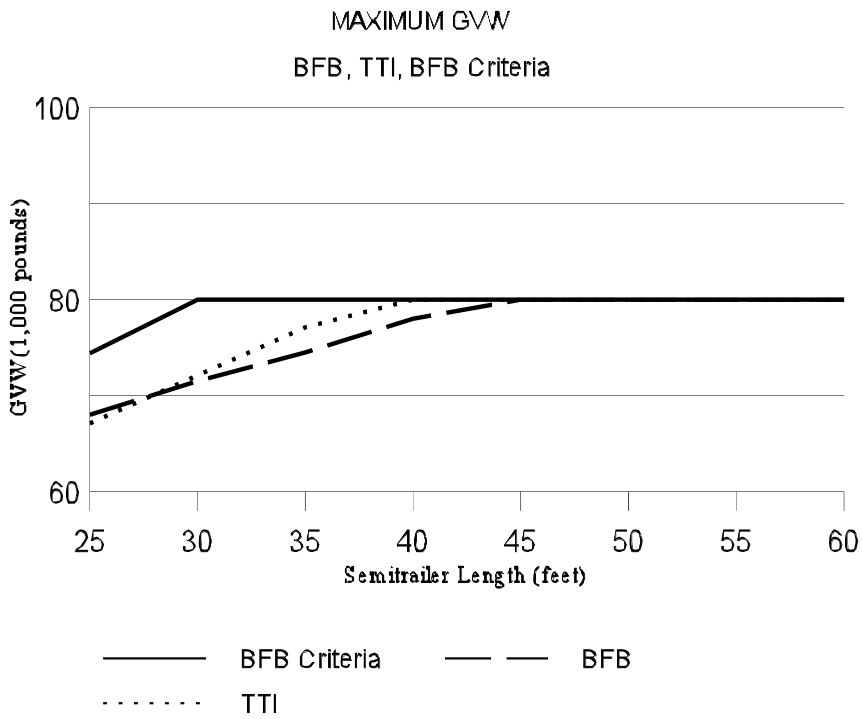
10 "Bridge Overstress Criteria," Michael Goshn, Charles G Schilling, Fred Moses, and Gary Runco, The City College of the City University of New York for the Federal Highway Administration, Washington, D.C., May, 1995.

**TABLE VI-2**
**MAXIMUM GVW FOR FIVE-AXLE SEMITRAILER COMBINATION APPLYING BFB, TTI, AND BFB STRESS CRITERIA**

22.5' Tractor Wheelbase, 52" Tractor Tandem Spread, and 48" Trailer Tandem Spread

| Semitrailer Length (feet) | Maximum GVW (1,000 Pounds) | | | Semitrailer Length (feet) | Maximum GVW (1,000 Pounds) | | |
|---|---|---|---|---|---|---|---|
| | BFB | TTI | BFB Stress Criteria | | BFB | TTI | BFB Stress Criteria |
| **23.0'** | 66.5 | 65.1 | 71.4 | **42.0'** | 79.5 | 80.0 | 80.0 |
| **24.0'** | 67.0 | 66.1 | 72.9 | **43.0'** | 80.0 | 80.0 | 80.0 |
| **25.0'** | 68.0 | 67.1 | 74.4 | **44.0'** | 80.0 | 80.0 | 80.0 |
| **26.0'** | 68.0 | 68.1 | 75.7 | **45.0'** | 80.0 | 80.0 | 80.0 |
| **27.0'** | 69.0 | 69.1 | 77.1 | **46.0'** | 80.0 | 80.0 | 80.0 |
| **28.0'** | 70.0 | 70.1 | 78.4 | **47.0'** | 80.0 | 80.0 | 80.0 |
| **29.0'** | 71.0 | 71.1 | 79.7 | **48.0'** | 80.0 | 80.0 | 80.0 |
| **30.0'** | 71.5 | 72.1 | 80.0 | **49.0'** | 80.0 | 80.0 | 80.0 |
| **31.0'** | 72.0 | 73.1 | 80.0 | **50.0'** | 80.0 | 80.0 | 80.0 |
| **32.0'** | 72.0 | 74.1 | 80.0 | **51.0'** | 80.0 | 80.0 | 80.0 |
| **33.0'** | 73.5 | 75.1 | 80.0 | **52.0'** | 80.0 | 80.0 | 80.0 |
| **34.0'** | 74.0 | 76.1 | 80.0 | **53.0'** | 80.0 | 80.0 | 80.0 |
| **35.0'** | 74.5 | 77.1 | 80.0 | **54.0'** | 80.0 | 80.0 | 80.0 |
| **36.0'** | 75.0 | 78.1 | 80.0 | **55.0'** | 80.0 | 80.0 | 80.0 |
| **37.0'** | 76.0 | 79.1 | 80.0 | **56.0'** | 80.0 | 80.0 | 80.0 |
| **38.0'** | 76.5 | 80.0 | 80.0 | **57.0'** | 80.0 | 80.0 | 80.0 |
| **39.0'** | 77.5 | 80.0 | 80.0 | **57.5'** | 80.0 | 80.0 | 80.0 |
| **40.0'** | 78.0 | 80.0 | 80.0 | **58.0'** | 80.0 | 80.0 | 80.0 |
| **41.0'** | 78.0 | 80.0 | 80.0 | | | | |

**FIGURE VI-2**
**COMPARISON FOR FIVE-AXLE SEMITRAILER COMBINATION**

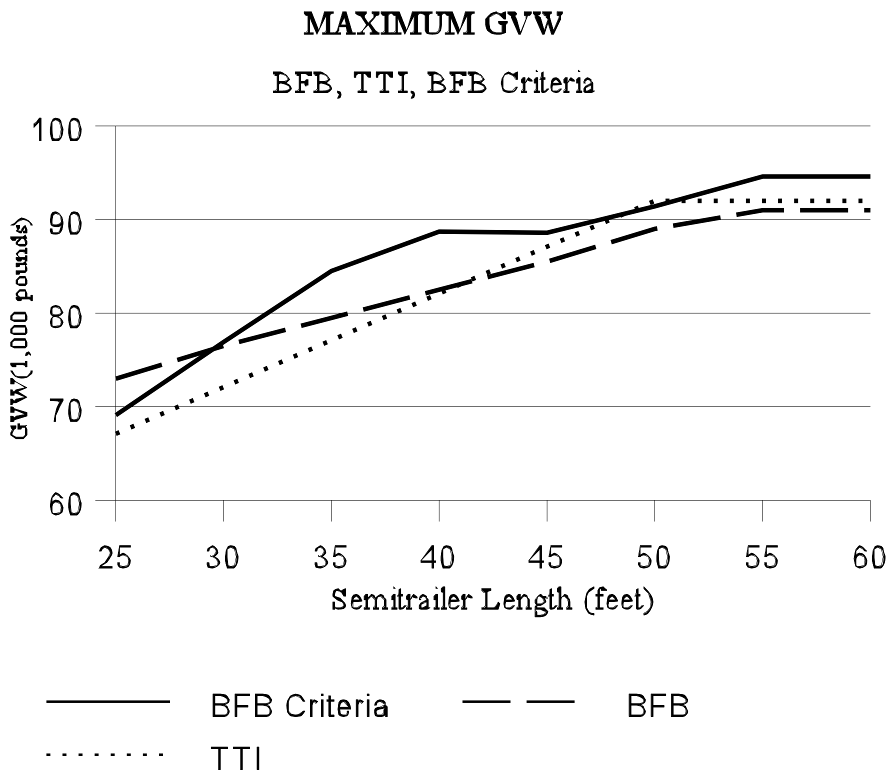


Illustrative Table VI-3 and Figure VI-3 have been created for a tractor-semitrailer combination vehicle with a three-axle tractor and a semitrailer supported at the rear by a tridem-axle group. In the case of the six-axle semitrailer, both the tractor wheelbase and semitrailer length are varied (common descriptive dimensions). Table VI-3 provides the GVW allowed under three formulas.

**TABLE VI-3**
**MAXIMUM GVW FOR SIX-AXLE SEMITRAILER COMBINATION APPLYING**
**BFB, TTI, AND BFB STRESS CRITERIA**
**22.5' TRACTOR WHEELBASE**

| Semitrailer Length (feet) | Maximum GVW (1,000 Pounds) | | | Semitrailer Length (feet) | Maximum GVW (1,000 Pounds) | | |
|---|---|---|---|---|---|---|---|
| | BFB | TTI | BFB Stress Criteria | | BFB | TTI | BFB Stress Criteria |
| 23.0' | 72.0 | 65.1 | 66.2 | 41.0' | 83.5 | 83.1 | 88.4 |
| 24.0' | 72.5 | 66.1 | 67.6 | 42.0' | 84.0 | 84.1 | 88.2 |
| 25.0' | 73.0 | 67.1 | 69.1 | 43.0' | 84.5 | 85.1 | 88.3 |
| 26.0' | 73.0 | 68.1 | 70.5 | 44.0' | 85.0 | 86.1 | 88.5 |
| 27.0' | 74.5 | 69.1 | 70.0 | 45.0' | 85.5 | 87.1 | 88.6 |
| 28.0' | 75.0 | 70.1 | 73.4 | 46.0' | 86.0 | 88.1 | 89.0 |
| 29.0' | 76.0 | 71.1 | 75.2 | 47.0' | 87.0 | 89.1 | 89.5 |
| 30.0' | 76.5 | 72.1 | 76.9 | 48.0' | 87.5 | 90.1 | 90.0 |
| 31.0' | 77.0 | 73.1 | 78.4 | 49.0' | 88.5 | 92.0 | 90.7 |
| 32.0' | 77.5 | 74.1 | 80.0 | 50.0' | 89.0 | 92.0 | 91.4 |
| 33.0' | 78.0 | 75.1 | 81.5 | 51.0' | 89.5 | 92.0 | 92.3 |
| 34.0' | 79.0 | 76.1 | 83.0 | 52.0' | 90.0 | 92.0 | 93.3 |
| 35.0' | 79.5 | 77.1 | 84.5 | 53.0' | 90.5 | 92.0 | 94.2 |
| 36.0' | 80.0 | 78.1 | 85.3 | 54.0' | 91.0 | 92.0 | 94.6 |
| 37.0' | 80.5 | 79.1 | 86.2 | 55.0' | 91.0 | 92.0 | 94.6 |
| 38.0' | 81.0 | 80.1 | 87.0 | 56.0' | 91.0 | 92.0 | 94.6 |
| 39.0' | 82.0 | 81.1 | 87.9 | 57.0' | 91.0 | 92.0 | 94.6 |
| 40.0' | 82.5 | 82.1 | 88.7 | 58.0' | 91.0 | 92.0 | 94.6 |

**FIGURE VI-3**
**COMPARISON FOR SIX-AXLE-SEMITRAILER COMBINATION**
(22.5' Tractor Wheelbase)

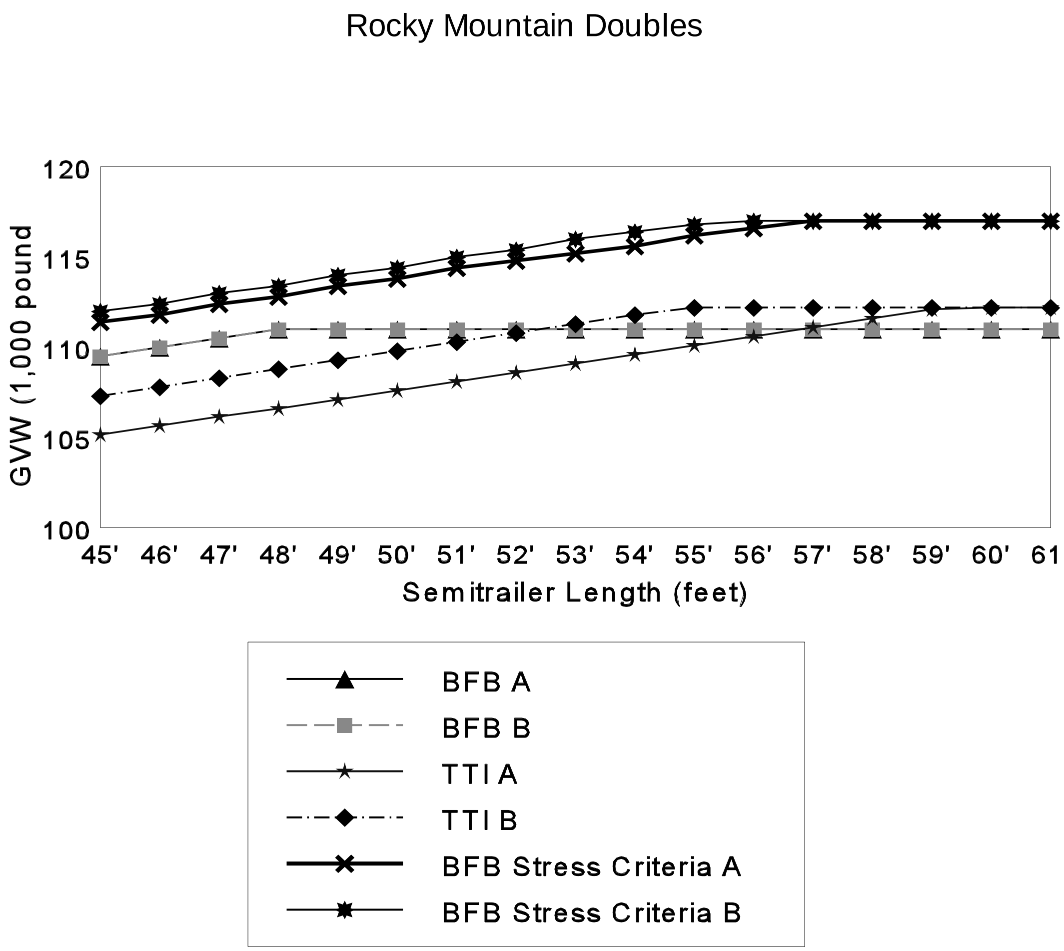


Illustrative Table VI-4 and Figure VI-4 present the values and charts the results for the Rocky Mountain double (RMD) combination which is a tractor-semitrailer combination with a three-axle tractor pulling a two-axle semitrailer and a two-axle full trailer. In the case of the RMD, the tractor and semitrailer length are varied, with the trailer remaining fixed at 28 feet. The limiting axle loads and maximum GVW for the entire vehicle are easily read from a table. This approach negates the need to compute the many axle group combinations inherent in the use of the existing and proposed formulas (which can amount to as many as 36 different combinations in the case of a nine-axle vehicle).

**TABLE VI-4**
**MAXIMUM GVW FOR RMD WITH SEMITRAILER OF VARIABLE LENGTH AND 28' TRAILER APPLYING BFB, TTI, AND BFB STRESS CRITERIA**
Tractor A = 18.2 feet or Tractor B = 22.5 feet

| Semitrailer Length (feet) | BFB GVW (1,000 pounds) | | TTI GVW (1,000 pounds) | | BFB Stress Criteria GVW (1,000 pounds) | |
|---|---|---|---|---|---|---|
| | Tractor A | Tractor B | Tractor A | Tractor B | Tractor A | Tractor B |
| 45' | 109.5 | 109.5 | 105.16 | 107.3 | 111.4 | 112 |
| 46' | 110 | 110 | 105.66 | 107.8 | 111.8 | 112.4 |
| 47' | 110.5 | 110.5 | 106.16 | 108.3 | 112.4 | 113 |
| 48' | 111 | 111 | 106.6 | 108.8 | 112.8 | 113.4 |
| 49' | 111 | 111 | 107.1 | 109.3 | 113.4 | 114 |
| 50' | 111 | 111 | 107.6 | 109.8 | 113.8 | 114.4 |
| 51' | 111 | 111 | 108.1 | 110.3 | 114.4 | 115 |
| 52' | 111 | 111 | 108.6 | 110.8 | 114.8 | 115.4 |
| 53' | 111 | 111 | 109.1 | 111.3 | 115.2 | 116 |
| 54' | 111 | 111 | 109.6 | 111.8 | 115.6 | 116.4 |
| 55' | 111 | 111 | 110.1 | 112.2 | 116.2 | 116.8 |
| 56' | 111 | 111 | 110.6 | 112.2 | 116.6 | 117 |
| 57' | 111 | 111 | 111.1 | 112.2 | 117 | 117 |
| 58' | 111 | 111 | 111.6 | 112.2 | 117 | 117 |
| 59' | 111 | 111 | 112.1 | 112.2 | 117 | 117 |
| 60' | 111 | 111 | 112.2 | 112.2 | 117 | 117 |
| 61' | 111 | 111 | 112.2 | 112.2 | 117 | 117 |

**FIGURE VI-4**
**RMD GVW COMPARISON CHART: BFB, TTI, BFB STRESS CRITERIA**
**Tractor A= 18.2 feet Tractor B= 22.5 feet**




A = Combination with Tractor A, B= Combination with Tractor B

The preceding charts clearly indicate the relationship between the controls for BFB, TTI and BFB Stress formula. The degree to which BFB and TTI correlate with the criteria on which they are based is clearly seen. Table VI-5 summarizes the findings based on application of the BFB, TTI, and BFB Stress Criteria to the three illustrative truck configurations: (1) the five-axle tractor-semitrailer (3-S2); (2) the six-axle tractor-semitrailer (3-S3); and the RMD.

**TABLE VI-5**
**APPLICATION OF BFB, TTI AND BFB STRESS CRITERIA**

**3-S2 Highlights**
(3-axle tractor and 2-axle semitrailer)

- The BFB Stress Criteria curve is more permissive than either the BFB or TTI formula. This allows shorter vehicles to carry more payload without violating the stress criteria on which BFB is based.
- The TTI formula is less permissive than BFB for the 23- to 25-foot axle spacing.
- The TTI is more permissive than BFB for the 26- to 42-foot axle spacing.
- All curves are constrained by axle limits, not the 80,000-pound GVW limit. It is only coincidental if the sum of the axles equals 80,000 pounds.
- Linearity is evident in the BFB and TTI curves, and although it appears to be present in the BFB Stress Criteria curve it is not. The ascending part of the curve of the BFB Stress Criteria actually curves downward in a slightly concave manner.

**3-S3 Highlights**
(3-axle tractor and tridem-axle semitrailer)

- The BFB is more permissive than both the TTI and BFB Stress Criteria curve in the 25- to 29-foot axle spacing.
- The TTI formula is less permissive than both BFB and BFB Stress Criteria curve for axle spacing up to 41 feet, and more permissive than BFB for spacing greater than 41 feet.
- BFB Stress Criteria curve is more permissive than TTI and BFB for axle spacing over 30 feet as the curves indicate, with the exception of the 40- to 51-foot range where it is the same as the TTI formula.
- The maximum limits for the longer trailer lengths and axle spacings vary for all three formulas. The BFB maximum limit is 91,000 pounds; the TTI maximum limit is 92,000 pounds; and the BFB Stress Criteria maximum limit is 94,600 pounds. The reason for the differences in GVW is the different weights allowed by each for the tridem-axle: BFB is 45,000 pounds; TTI is 46,000 pounds; and BFB Stress Criteria is 48,600 pounds (constrained by simple beam stress levels). All curves are calculated using 12,000 pounds for the steering axle and 34,000 pounds for the tractor tandem-axle.
- The BFB Stress Criteria formula results in a curvilinear relationship that is pronounced. This is due to the variation in stress at the center pier of a two-span continuous bridge and shape of the influence line for that stress. The actual physical phenomenon occurring in bridges cannot be matched with linear curves with either the BFB or TTI formulas, although at the higher limits TTI comes closer than BFB .
- The 80,000 pound GVW limit is reached before the axle-limits are exceeded for this configuration with all three formulas.

**RMD Highlights**

- The BFB Stress Criteria curve results in a more liberal (permissive) curve than the BFB or TTI formulas.
- Two tractor lengths are used for the analysis resulting in increased payload for axle spacing up to 51 feet under the BFB Stress Criteria and TTI formulas. BFB is constrained by the inner axle groupings for both vehicle combinations with the steering axle limited at 12,000 pounds.
- The BFB formula is more permissive than the TTI formula for axle spacing up to 52 feet. Tractor B is more permissive with axle spacing up to 56 feet and Tractor B is more permissive for spacing more than 56 feet.
- For the maximum limits, the BFB Stress Criteria curve allows the greatest weight to be carried, followed by TTI and BFB in that order.
- The linearity of the BFB and TTI is strongly evident in the curves, whereas the BFB Stress Criteria formula relationship is curvilinear for spacing between 53 and 56 feet. The TTI formula curve is closer fit to the BFB Stress Criteria curve then the BFB curve.

In summary, there is significant variation in the results (curves) that is dependent on vehicle configuration. In general, the TTI formula is better match than the BFB formula for bridges and there is a significant amount of load capacity available before limits are exceeded for the three configurations. However, this is not the case for the largest vehicles--the BFB allows too much weight for turnpike doubles. The TTI curve for that vehicle is on the low side of the BFB Stress Criteria curve. Also, the BFB formula is too liberal for multi-axle short straight trucks.

There are demonstrative benefits to adhering to the criteria on which BFB is based, and incorporating the consideration of continuous beams into the control. Tools, such as user friendly computer programs can be used to assess allowable loading configurations for any vehicle, and standard (bridge formula) tables for the more common vehicles can be generated and made available.

The alternative described in this section squarely addresses the documented drawbacks of BFB and provides a basis for truck weight control that conforms to the criteria upon which both BFB and TTI are based but do not adhere to.

It should be noted that Federal BFB, by design, incorporates a degree of control for pavement damage by explicitly including the number of axles in the formula. The TTI and the BFB Stress Criteria formulas indirectly control for pavement damage by adhering to axle weight limits--the higher GVW limits, such as for LCVs, require more axles to avoid exceeding axle limits.

The quantitative analyses in CTS&W Study Volume III evaluate other options that are not constrained to the BFB stress criteria. Allowable weight for other stress levels could be easily developed using the same methods used to develop the BFB stress criteria weights.

## PAVEMENT IMPACTS

The condition and performance of highway pavement is dependent on many factors, including: thickness of the various pavement layers, quality of construction materials and practices, maintenance, properties of the roadbed soil, environmental conditions (most importantly rainfall and temperature), and the number and weights of axle loads to which the pavements are subjected.[11]

[11] TRB *Special Report 225, Truck Weight Limits: Issues and Options,* 1990.

## IMPACT OF AXLES

### WEIGHT

Load equivalency factors, such as equivalent single-axle loads (ESAL), measure the relative effects of different types of loadings on pavements. Pavement engineers generally use the concept of an ESAL to measure the effects of axle loads on pavement. By convention, an 18,000-pound single axle equals 1.0 ESAL. The ESAL values for other axles express their effect on pavement wear relative to the 18,000-pound single axle. The effect of a given vehicle on pavements can be estimated by calculating the number of ESALs for each axle, adding the ESALs to obtain the total ESALs for the vehicle. For example, if a given vehicle on a given type of pavement is 3.0 ESALs, then one pass by the vehicle has the same effect on that pavement as three passes by an 18,000-pound single axle.

AASHTO provides separate sets of ESAL values for flexible and rigid pavements. The principal difference between the flexible and rigid pavement ESAL values is that tandem axles were found to have a greater effect on rigid pavements as Figures VI-5 and VI-6 illustrate. For example, a 34,000-pound tandem axle is about 1.1 ESALs on flexible pavement and about 2.0 ESALs on rigid pavements. The same is true of single axles.

**FIGURE VI-5**
**AXLE LOAD EFFECTS ON FLEXIBLE PAVEMENT**

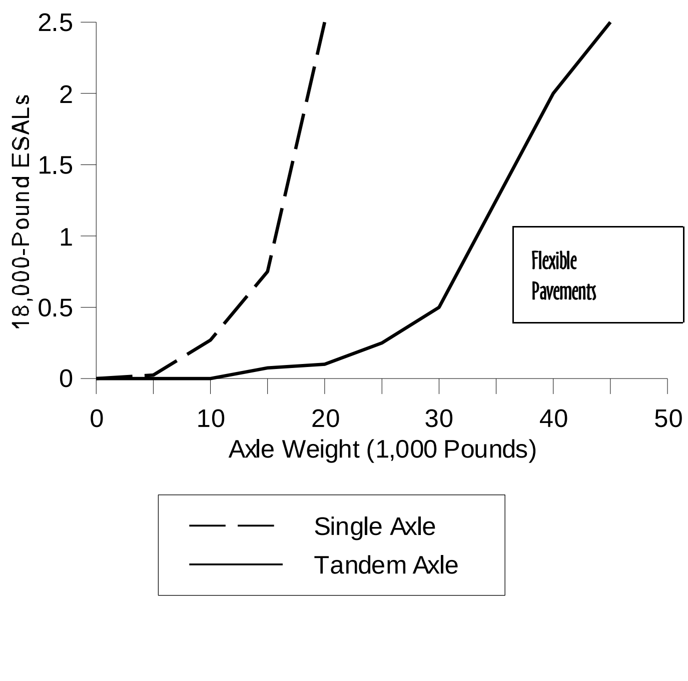
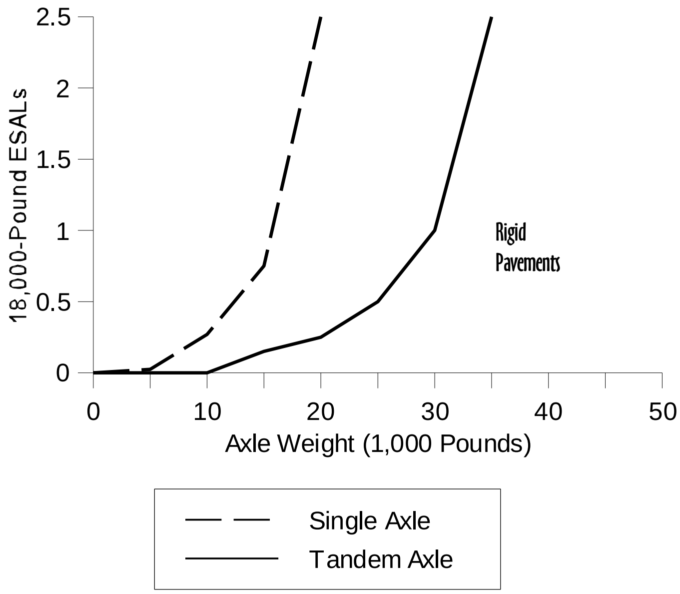


**FIGURE VI-6**
**AXLE LOAD EFFECT ON RIGID PAVEMENT**




While pavement engineers traditionally have used ESAL factors estimated from the AASHO Road Test as the basis for designing pavements, there is increasing recognition that better relationships between axle load and pavement wear are needed. Pavement distress models used in both the 1982 and the 1997 Federal HCA Study abandoned the use of ESALs to relate axle loading to pavement wear, and AASHTO will be replacing its ESAL-based pavement design formula with one that more directly relates axle loads to factors that determine pavement life. While ESALs are not used as the basis for estimating pavement costs associated with different TS&W scenarios, they are widely understood by highway administrators, pavement engineers, and others concerned about pavement impacts of TS&W scenarios and will be used as a benchmark for comparing relative pavement impacts among different truck configurations with different numbers and types of axles.

Pavement wear increases sharply with increases in axle load. On both flexible and rigid pavements, the load-equivalence factor for a 20,000-pound single axle is about 1.5. Thus, 100 passes across a pavement by a 20,000-pound axle would have the same effect on pavement life as 150 passes by an 18,000-pound axle.

The number of axles is also important in estimating pavement impact: other things being equal, a vehicle with more axles has less effect on pavements. For example, a nine-axle combination vehicle carrying 80,000 pounds has less of an effect on pavements than a five-axle combination vehicle carrying 80,000 pounds. A significant amount of additional weight can be carried by the nine-axle vehicle without causing greater pavement consumption relative to the five-axle vehicle.

A comparison of vehicles in terms of ESALs provides information on load-related pavement impact, but it does not factor in an offsetting benefit gained by a reduction in the number of trips required to transport the same amount of freight. Vehicles are often compared in terms of ESALs per unit of freight carried as a means of factoring in the reduction in pavement wear from fewer trips.

The increase in pavement costs per added ESAL mile can vary by several orders of magnitude depending upon pavement thickness, quality of construction, and season of the year. Thinner pavements are much more vulnerable to traffic loadings than thicker pavements[12]. Additionally, pavements are much more vulnerable to traffic loadings during spring thaw in areas that are subject to freeze-thaw cycles.

## AXLE SPACING

The primary load effect of axle spacing on flexible pavement performance is fatigue. Axle spacing is a major concern for fatigue. When widely separated loads are brought closer together, the stresses they impart to the pavement structure begin to overlap and they cease to act as separate entities. While the maximum deflection of the pavement surface continues to increase as axle spacing is reduced, maximum tensile stress at the underside of the surface layer (considered to be a primary cause of fatigue cracking) can actually decrease as axle spacing is reduced. However, effects of the overlapping stress contours also include increasing the duration of the loading period. Thus, the beneficial effects of stress reduction are offset to some largely unknown degree by an increase in the time or duration of loading. The net effect of changes in axle spacing on pavement wear is complex and highly dependent on the nature of the pavement structure.[13]

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[12] Results of a study by Hutchinson and Haas compare the average and marginal costs per ESAL on highways with 500,000 ESALs per year and 2,000,000 ESALs per year. They indicate the cost per ESAL for highways with 500,00 ESALs is almost four times as great as the cost per ESAL on highways designed for 2,000,000 ESALs. One important implication of this finding is that a policy that encourages heavy trucks to shift from highways with thicker pavements, such as the Interstate or NHS, to highways with thinner pavement can have a significant impact on pavement costs.

[13] TRB *Special Report 225, Truck Weight Limits: Issues and Options,* 1990.

## TIRE CHARACTERISTICS

In recent years several studies on the impact of tire characteristics on pavement have raised concern over the possibility of accelerated pavement wear, particularly rutting, caused by increasing tire pressures. The tires of the AASHO Road Test trucks of the 1950s were bias-ply construction with inflation pressures between 75 pounds and 80 pounds per square inch (psi). The replacement of bias-ply tires with radial tires and higher inflation pressures, averaging 100 psi[14], result in a smaller size tire "footprint" on the pavement and consequently concentration of weight over a smaller area. The increased pressures hasten the wear of flexible pavements, increasing both the rate of rutting and the rate of cracking.

The AASHTO load-equivalency factors strictly apply only to axles supported at each end by dual tires. Recent increases in steering-axle loadings and more extensive use of single tires on load-bearing axles have precipitated efforts to examine the effect on pavement wear of substituting single for dual tires. Both standard and wide-based tires have been considered. Past investigations of the pavement wear effects of single versus dual tires have found that single tires induce more pavement wear than dual tires, but that the differential wear effect diminishes with increases in pavement stiffness, in the width of the single tire, and in tire load.[15]

A general finding from the studies is that wide-base single tires appear to cause about 1.5 times more rutting than dual tires on roadways that do not possess good resistance qualities to rutting, such as flexible pavement, by far the most common type of pavement. Another finding is that one of the wheels in a dual tire assembly is frequently overloaded due to the road and that the average overload causes an increase in rutting similar to that caused by wide-based single and dual tire assemblies. Therefore, the real advantage of dual tire assemblies is undoubtedly lower than the theoretical advantage attributed to their use.[16]

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[14] A study by Bartholomew (1989) summarized surveys of tire pressure conducted in seven States between 1984 and 1986 and found that 70 to 80 percent of the truck tires used were radials and that average tire pressures were about 100 psi.

[15] Gillespie (1993) found that a steering axle carrying 12,000 pounds with conventional single tires is more damaging to flexible pavements than a 20,000-pound axle with conventional dual tires. Gillespie proposed that road damage from an 80,000-pound vehicle combination would be decreased by approximately 10 percent if a mandated load distribution of 10,000 pounds on the steering axle and 35,000 pounds on tandems. Since the operating weight distribution of a five-axle tractor-semitrailer at 80,000 pounds GVW generally has less than 11,000 pounds on the steering axle, the practical effect of the proposal would be to increase tandem axle weights without a compensating decrease in steering axle weights.

[16] Conflicting results were reported by Akram, et. al. They used multi-depth deflectometers to estimate the damage effects of dual versus wide-based tires. Deflections measures at several depths within the pavement under dual and wide-base single tires were used to calculate average vertical compressive strains. The Asphalt Institute's (AI) subgrade limiting strain criteria were then used to estimate the reduction in pavement life that will occur by using the wide-based single tires in place of duals. At a speed of 55 miles per hour, and equivalent axle loading, the AI found that the wide-based single tires (trailer axle) reduced the anticipated pavement life by a factor between 2.5 and 2.8 over that predicted for standard dual tires.

Based upon past studies single tires have more adverse effects on pavements than dual tires, it appears likely that past investigations have overstated the adverse effects of single tires[17] by neglecting two potentially important effects: (1) unbalanced loads between the two tires of a dual set, and (2) the effect of randomness in the lateral placement of the truck on the highway. Unbalanced loads between the tires of a dual set can occur as a result of unequal tire pressures, uneven tire wear, and pavement crown. As with unequal loads on axles within a multi-axle group, pavement wear increases as the loads on the two dual tires become more unbalanced.

The second neglected factor, sometimes termed "wander," is the effect of randomness in the lateral placement of trucks within and sometimes beyond lane boundaries. Less perfect tracking is beneficial to pavement wear, as the fatiguing effect is diminished because the repetitive traffic loads are distributed over wider areas of the pavement surface. Because the greater overall width of dual tires naturally subjects a greater width of pavement to destructive stresses, wander is expected to have a smaller beneficial effect for dual than for single tires. Once rutting begins, however, tires, especially radial tires, tend to remain in the rut, thereby greatly reducing the beneficial effects of wander for both single and dual tires[18] (see Figure VI-7).

The TRB *Special Report 225* found that without wander, the ESAL equivalent for an 18,000-pound axle with single tires was estimated to be 2.23. When wander with a standard deviation of 8 inches is assumed, the ESAL equivalent drops to 1.31. At least for the plus or minus 5 percent case considered in this study, the effects of imbalance in dual-tire sets on ESALs were found to be very small relative to the effect of wander.

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[17] Bauer (1994) summarized several recent studies on the effects of single versus dual tires: "Smith (1989), in a synthesis of several studies... evaluated at 1.5 on average the relationship of the damage caused by wide base single assemblies and that caused by traditional dual tire assemblies with identical loading at the axle. Sebaaly and Tabataee (1992) found rutting damage ratios between wide base and dual tire assemblies varying between 1.4 and 1.6....Bonaquist (1992), reporting on results obtained from a study ...on two types of roadway, using a dual tire assembly with 11 R 22.5 and a wide base with 425/65 R 22.5, indicates rutting damage ratios varying from 1.1 to 1.5, depending on the layers of the roadway."

[18] The TRB *Special Report 225* examined the importance of loading imbalance and wander. The TRB study examined two types of pavement wear: surface cracking due to fatigue and permanent deformation or rutting in the wheel tracks. Fatigue was found to be more sensitive to the differences between single and dual tires than rutting. Both balanced and unbalanced dual-tire loads were considered in analyzing the affect on wander. The analysis indicated that the adverse effects of single tires on pavement wear were reduced when wander was taken into account, although the effects were still significant.

Another consideration in evaluating wide-base single versus dual tires is dynamic loadings that arise from the vertical movement of the truck caused by surface roughness. Thus, peak loads are applied to the pavement that are greater than the average static load.[19] Signs of pavement damage from dynamic loadings are typically localized, at least initially. Because of the localized nature of the dynamic loading, its severity is much greater than previously thought.[20] A further note on wide-base single tires is that those having only two sidewalls are much more flexible than a pair of dual tires with four sidewalls, which means the tire absorbs more of the dynamic bouncing of the truck and less of the dynamic load is transmitted to the pavement.

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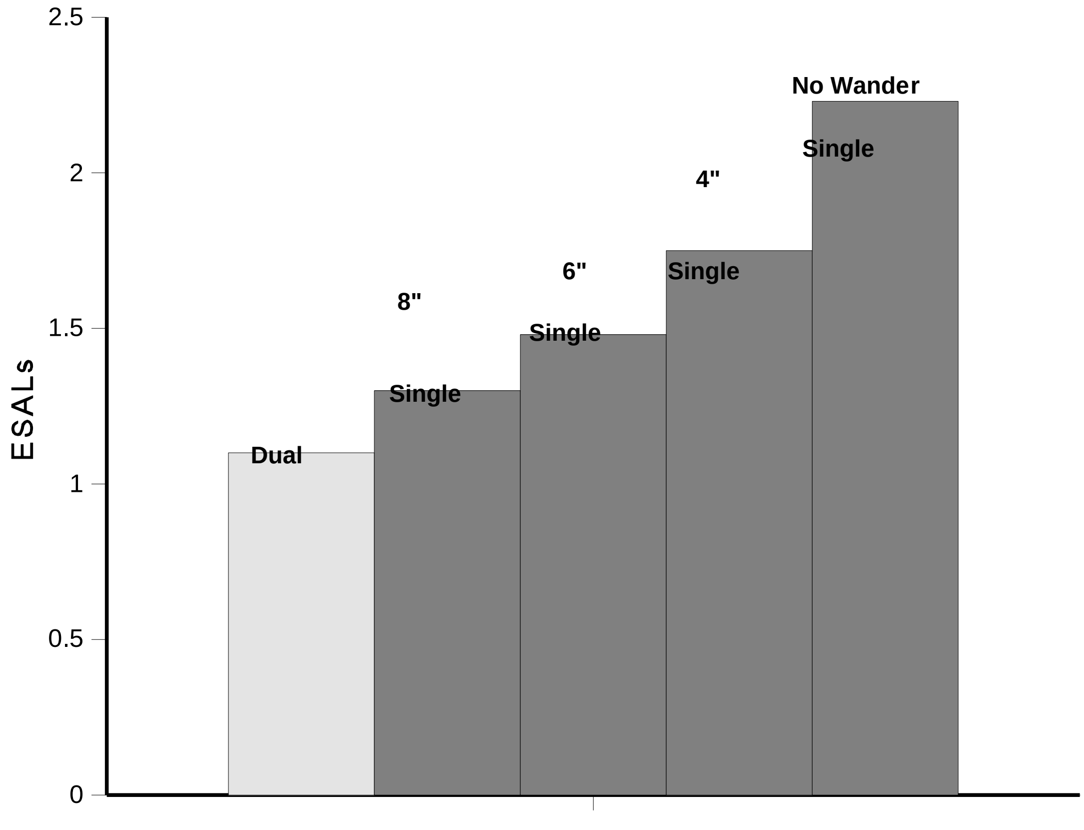
[19] From research summarized by the Midwest Research Institute (MRI) that suggests dynamic loadings are a consideration in assessing the relative merits of wide base single versus dual tires. Gyenes and Mitchell report that the magnitude of the added dynamic components was earlier thought to increase road damage over that of the static loading alone between 13 and 38 percent, according to research reported by Eisenmann. The MRI research noted that many recent studies have pointed out the fallacy in the earlier work, which assumed that the dynamic component of loading was distributed uniformly over the pavement in the direction of travel. The research found, however that the dynamic component is very localized, arising out of pavement surface irregularities and therefore is spatially correlated with these irregularities.

[20] Gillespie, et.al. estimate that damage due to the combination of static and dynamic loading can be two to four times that due to static loading locally. Von Becker estimates the combined loading produces a “shock factor” between 1.3 and 1.55, depending upon suspension characteristics. Applying the fourth power law would translate these figures into relative damage estimates ranging from 2.8 to 4.8 times the static loading damage. Gyenes and Mitchell suggest impact factors in the range of 1.3 to 1.5 for relative damage estimates of 2.8 to 5.1.

**FIGURE VI-7**
**THE EFFECT OF SINGLE TIRES VS DUAL TIRES ON PAVEMENT**
**18,000 pound Single Axle (wander is in standard deviations)**




Source: TRB *Special Report 225, Truck Weight Limits: Issues and Options*

## SUSPENSION SYSTEMS

The subject of road-friendly suspensions (within the context of the broader subject of vehicle-pavement interaction) is under intensive research by an Organization for Economic Cooperation and Development (OECD) project involving the United States and 16 other countries.[21] The work is focusing on: (1) how well different suspension systems can distribute load between axles in a group (the more evenly, the better); (2) how well different suspension systems dampen vertical dynamic loads (the more, the better); and (3) spatial repeatability of dynamic loads. Related considerations are examining how road and bridge characteristics act to excite a truck, and in turn influence the loads received by the road and bridge.

Recent research[22] on the role that suspension damping plays in enhancing the road friendliness of a heavy vehicle found that an increase in linear suspension damping tends to reduce the dynamic load coefficient and the dynamic tire forces, factors related to road wear. a conclusion was made that linear and air spring suspensions with light linear damping offer significant potentials to enhance the road friendliness of the vehicle with a slight deterioration in ride quality.[23] It is worth noting that approximately 90 percent of all truck tractors and 70 percent of all van trailers sold in the United States are equipped with air suspensions. Additional studies on various types of axle suspension systems include studies on: torsion suspensions, four-leaf suspensions, and walking-beam suspensions.[24]

The research has yet to produce any compelling argument to incorporate a suspension system determinant into United States regulations although some countries have done so. Mexico is in the final stages of preparing regulations that will allow up to 2,200 pounds of additional weight for each trailer axle equipped with an air suspension or its equivalent. For a drive axle, Mexico may allow up to an additional 3,300 pounds. The impacts of different suspension systems on

[21] TRB *Special Report 225* noted that a heavy truck travels along the highway, axle loads applied to the pavement surface fluctuate above and below their average values. The degree of fluctuation depends on factors such as pavement roughness, speed, radial stiffness of the tires, mechanical properties of the suspension system, and overall configuration of the vehicle. On the assumption that the pavement wear effects of dynamic loads are similar to those of static loads and follow a fourth-power relationship, increases in the degrees of fluctuation increase pavement wear.

[22] Rakheja and Woodrooffe.

[23] In the Rakheja and Woodroofe model suspension effects are represented using a sprung mass, an unsprung mass, and restoring and dissipative effects due to suspension and tire. The tire is modeled assuming linear spring rate, viscous damping, and point contact with the road.

[24] Sousa, Lysmer and Monismith investigated the influence of dynamic effects on pavement life for different types of axle suspension systems. They calculated a Reduction of Pavement Life (RPL) index of 19 percent for torsion suspensions (an ideal suspension would have RPL of 0). Similar results were found by Peterson in a study for Road and Transport Association of Canada: under rough roads at 50 mph, air bag suspensions exhibited dynamic loading coefficients (DLC) of 16 percent, spring suspensions had a DLC of 24 percent, and rubber spring walking beam suspensions had a DLC of 39 percent. Problems with walking-beam suspensions were also noted by Gillespie, et.al. who state that on rough and moderately rough roads, walking-beam suspensions without shock absorbers are typically 50 percent more damaging than other suspension types.

pavement deterioration are of secondary importance compared to the static axle load levels themselves. Use of road-friendly suspensions is beneficial, particularly for large trucking operations with well-controlled axle loadings.

### LIFT AXLES

The widespread use of lift axles in both Canada and the United States has raised concerns for pavement wear caused by a lift axle being in a raised position and the potential misuses that result when a driver, attempting to improve fuel consumption, fails to lower the axle when loaded. A survey conducted in Canada[25] in 1988 and 1989 in Ontario and Quebec found that approximately 17 percent and 21 percent, respectively, of trucks on highways in those provinces had lift axles. Lift axles have been adopted in response to GVW limits that are governed by the number of axles and because trucks with multiple, widely spaced axles have difficulty turning on dry roads and the lift axles can be raised by the driver prior to turns.

Lift axles make compliance with and enforcement of axle weight limits difficult. There are many concerns about the use of lift axles and damage to roads and bridges. Improperly adjusted lift axles can be damaging to pavements. The lift axle can be adjusted to any level by the driver. If the lift axle load is too high, the lift axle is overloaded. If it is too low, other axles may be overloaded. For example, under current Federal limits, a four-axle single-unit truck with a wheelbase of 30 feet can carry 62,000 pounds: 20,000 pounds on the steering axle and 42,000 pounds on the rear tridem. This vehicle would produce approximately 2.1 ESALs on flexible pavements. However, if the first axle of the tridem is a lift axle that is carrying little or no weight, this vehicle would produce approximately 4.0 ESALs.

## PAVEMENT IMPACT

The pavement impacts for this study were estimated by using the Nationwide Pavement Cost Model (NAPCOM). NAPCOM incorporates 11 different pavement distress models. Together these models represent the state-of-the-art in predicting pavement responses to different axle loads and repetitions at the National level.

Pavement design parameters for each State, such as soil strength, terminal PSI value and other considerations are considered in this analysis. Design methods reflect the latest State specific and AASHTO design manuals and guidelines. Costs are estimated for traffic on each highway functional class based upon analyses and over 100,000 pavement sections in the HPMS database.

### UNIT PAVEMENT COSTS

Unit pavement costs and pavement costs per unit of payload-mile by configuration are shown in Table VI-6 and Table VI-7. They illustrate how the addition of axles allows for increased payloads and at the same time reduces pavement wear. Particularly striking, are comparisons

[25] Billing, et.al.

between the three- and four-axle single unit trucks, the five- and six-axle semitrailer combinations, and the five- and eight-axle doubles. The four-axle truck has costs per payload ton-mile about 75 percent of that for the three-axle truck even though its gross weight is 10,000 pounds more than the three-axle truck. The comparison of the six-axle semitrailer with the five-axle is very similar. The costs for the eight-axle double are less than half those for the five-axle double. Triples do not compare well with the doubles, however. It should be noted, however, that truck owners would be opposed to adding axles because it increases the tare weight of the vehicle and reduces payload capacity. The benefits of increased numbers of axles insofar as pavement damage is concerned, as shown in Table VI-6 and Table VI-7 assume increases in the allowable gross vehicle weight.

**TABLE VI-6**
**UNIT PAVEMENT COST FOR VARIOUS TRUCK CONFIGURATIONS**

| Truck Configurations | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Area Type | Truck Type | Single Unit | | Semitrailer | | Double-Trailer | | | Triple | |
| | Axles | Three | Four | Five | Six | Five | Seven | Eight | Seven | |
| | GVW (pounds) | 54,000 | 64,000 | 80,000 | 90,000 | 80,000 | 100,000 | 105,000 | 100,000 | 115,000 |
| | $/1,000 miles | | | | | | | | | |
| | Functional Class | | | | | | | | | |
| Rural | Interstate | 0.09 | 0.07 | 0.05 | 0.05 | 0.03 | 0.10 | 0.05 | 0.04 | 0.08 |
| | Prin. Art. | 0.17 | 0.16 | 0.12 | 0.11 | 0.07 | 0.15 | 0.10 | 0.17 | 0.31 |
| | Min. Art. | 0.37 | 0.33 | 0.29 | 0.22 | 0.32 | 0.41 | 0.21 | 0.39 | 0.75 |
| | Maj. Col. | 1.38 | 1.35 | 0.90 | 0.80 | 1.17 | 1.03 | 0.65 | 1.46 | 2.95 |
| | Min. Col. | 2.27 | 2.08 | 1.49 | 1.24 | 1.92 | 1.69 | 1.07 | 2.42 | 4.87 |
| | Locals | 5.90 | 5.63 | 3.87 | 3.23 | 4.99 | 4.40 | 2.79 | 6.27 | 12.60 |
| Urban | Interstate | 0.06 | 0.04 | 0.04 | 0.04 | 0.03 | 0.04 | 0.02 | 0.03 | 0.05 |
| | Fwy&Ewy | 0.09 | 0.06 | 0.06 | 0.05 | 0.04 | 0.07 | 0.04 | 0.09 | 0.18 |
| | Prin. Art. | 0.13 | 0.12 | 0.10 | 0.09 | 0.11 | 0.09 | 0.06 | 0.13 | 0.26 |
| | Min. Art. | 0.30 | 0.24 | 0.22 | 0.17 | 0.19 | 0.18 | 0.12 | 0.34 | 0.70 |
| | Collectors | 0.66 | 0.70 | 0.54 | 0.49 | 0.46 | 0.34 | 0.25 | 0.86 | 1.82 |
| | Locals | 2.34 | 2.53 | 1.91 | 1.75 | 1.64 | 1.19 | 0.88 | 3.06 | 6.45 |

## TABLE VI-7
## UNIT COST PER PAYLOAD-MILE FOR VARIOUS TRUCK CONFIGURATIONS

| Truck Configuration | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Area Type** | **Truck Type** | **Single Unit** | | **Semitrailer** | | **Double-Trailer** | | | **Triple** | |
| | Axles | Three | Four | Five | Six | Five | Seven | Eight | Seven | |
| | GVW (pounds) | 54,000 | 64,000 | 80,000 | 90,000 | 80,000 | 100,000 | 105,000 | 100,000 | 115,000 |
| | Tare Weight | 22,600 | 26,400 | 30.490 | 31,530 | 29,320 | 38,600 | 33,470 | 41,700 | 41,700 |
| | Payload Weight | 31,400 | 37,600 | 49,510 | 58,470 | 50,680 | 61,400 | 71,530 | 58,300 | 73,300 |
| | **$/1,000 ton-miles** | | | | | | | | | |
| | **Functional Class** | | | | | | | | | |
| **Rural** | Interstate | 0.006 | 0.004 | 0.002 | 0.002 | 0.001 | 0.003 | 0.001 | 0.001 | 0.002 |
| | Prin. Art. | 0.011 | 0.009 | 0.005 | 0.004 | 0.003 | 0.005 | 0.003 | 0.006 | 0.008 |
| | Min. Art. | 0.024 | 0.018 | 0.012 | 0.008 | 0.013 | 0.013 | 0.006 | 0.013 | 0.020 |
| | Maj. Col. | 0.088 | 0.072 | 0.036 | 0.027 | 0.046 | 0.034 | 0.018 | 0.050 | 0.080 |
| | Min. Col. | 0.145 | 0.111 | 0.060 | 0.042 | 0.076 | 0.055 | 0.030 | 0.083 | 0.133 |
| | Locals | 0.376 | 0.299 | 0.156 | 0.110 | 0.197 | 0.143 | 0.078 | 0.215 | 0.344 |
| **Urban** | Interstate | 0.004 | 0.002 | 0.002 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| | Fwy&Ewy | 0.006 | 0.003 | 0.002 | 0.002 | 0.002 | 0.002 | 0.001 | 0.003 | 0.005 |
| | Prin. Art. | 0.008 | 0.006 | 0.004 | 0.003 | 0.004 | 0.003 | 0.002 | 0.004 | 0.007 |
| | Min. Art. | 0.019 | 0.013 | 0.009 | 0.006 | 0.007 | 0.006 | 0.003 | 0.011 | 0.019 |
| | Collectors | 0.042 | 0.037 | 0.022 | 0.017 | 0.018 | 0.011 | 0.007 | 0.030 | 0.050 |
| | Locals | 0.149 | 0.136 | 0.077 | 0.060 | 0.065 | 0.039 | 0.024 | 0.105 | 0.176 |

## CONSIDERATIONS RELATED TO PAVEMENT REGULATION

### TIRE REGULATIONS

Federal law and most States laws do not address truck tire pressure. Tire pressure may have a large effect on fatigue of flexible pavements as discussed earlier (albeit a small to moderate effect on rigid pavements) and today's tire pressures are higher than in the 1950s--primarily the consequence of a change from bias to radial ply tires. Concern has been raised about accelerated pavement rutting as a result of increased tire pressures. The research in recent years gives conflicting views as to whether or not pressures should be regulated.[26]

Federal, and most State, laws do not discourage or prohibit the use of wide-base tires. The consensus of U.S. and international research is that these tires have substantially more adverse effects on pavements than dual tires because current designs employ smaller, overall tire-road contact patch sizes than equivalent dual tire sizes. Future tire designs could address this issue. Wide-base tires--widely used in Europe--are being increasingly adopted by U.S. trucking operations. The benefits of wide-base tires are reduced energy use, emissions, tare weights, and truck operating costs. The trade-off between changes in Federal pavement costs and operating benefits that would result from permitting or prohibiting extensive adoption of wide-base tires in the United States has not been analyzed.

Many State laws do specify some form of tire load regulation to control the damage effect of wide-base tires. They restrict the weight that can be carried on a tire based on its width. The limits range from 550 pounds per inch (in Alaska, Mississippi, and North Dakota) to 800 pounds per inch (in Indiana, Massachusetts, New Jersey, New York, and Pennsylvania). Such restrictions result in lower pavement costs; however, the size of the pavement cost savings (either in absolute terms or in relation to the increase in goods movement costs also resulting from these restrictions) have not been estimated. This type of approach does, however, hold promise.

### SPLIT-TANDEM VERSUS TRIDEM-AXLE LOAD LIMITS

There is increasing use of wide-spread (up to 10 feet) “split-tandem” axle groups, particularly in flatbed heavy haul operations. These axles are allowed to be loaded at single axle limits--20,000 pounds on each of the two axles as opposed to 34,000 pounds on a closed tandem. They offer two key benefits to five-axle tractor-semitrailer usage: (1) flexibility in load distribution; and (2) full achievement of the 80,000-pound GVW cap, which is limited by the ability to distribute up

[26] TRB *Special Report 225* (1990) suggested regulation could be warranted if the more pessimistic analyses proved to be correct. NCHRP study (1993) suggested limiting tire pressure to the recommended cold setting plus 15-psi; AASHTO (1993) suggested more research is required to answer all questions regarding the relationship of tire size, contact pressure, and contact area to pavement damage.

to 12,000 pounds on the steering axle of a combination. But they do so with significant pavement cost. Their expanding use could be counteracted with a higher tridem-axle load to the benefit of pavements.[27]

In the United States, the allowable load on a group of three axles connected through a common suspension system (a tridem) is determined by the Federal bridge formula rather than a limit set by law (or regulation). In Europe, Canada, Mexico and most other jurisdictions, tridem axles are given a unique load limit in the same way the United States specifies unique single- and tandem-axle limits without direct reference to a bridge formula. This is not to say that these unique tridem limits are not bridge-related. In Canada, for example, the tridem limits prescribed by the Road Transport Association of Canada (RTAC), which vary as a function of spacing, are based on bridge loading limitations--not pavement limitations.

## THE GROSS VEHICLE WEIGHT LIMIT

The 80,000-pound GVW limit (cap) is the existing legal Federal maximum GVW limit for the Interstate Highway System, although some States allow truck combination weights above the cap under grandfather rights. Axle weight limits and BFB are designed to protect pavements and bridges respectively. As such, the cap may not be providing any additional protection to pavements and bridges. Nevertheless, it is important to consider such factors as bridge design vehicles and criteria, structural evaluation procedures, the age of the existing bridges and the extent to which increased GVWs would affect the fatigue life of bridges in the United States.

## 44,000-POUND TRIDEM-AXLE WEIGHT LIMIT

Original research, done for this study, on the pavement and bridge impacts of tridem axles showed how bridge stresses decrease as the axles in the tridem group are spread apart. This allows more weight to be carried on the tridem group as the axles are spread. The opposite is true for pavement damage. The more the axles are spread the greater the damage. Therefore, as the axles are spread within the group, the allowable weight must be reduced to hold pavement damage constant.

The tridem-axle weight limit of 44,000 pounds was determined by observing where the curve of the increasing bridge allowable load function crosses the curve of the decreasing pavement load equivalency function (see Figure VI-9). The two curves cross at a spread of 9 feet between the two outer axles which gives 44,000 pounds for both functions. To stop short of nine feet would require a lower load limit as bridge damage would be greater than at 44,000 pounds. To go beyond 9 feet would increase pavement damage over that at 44,000 pounds.

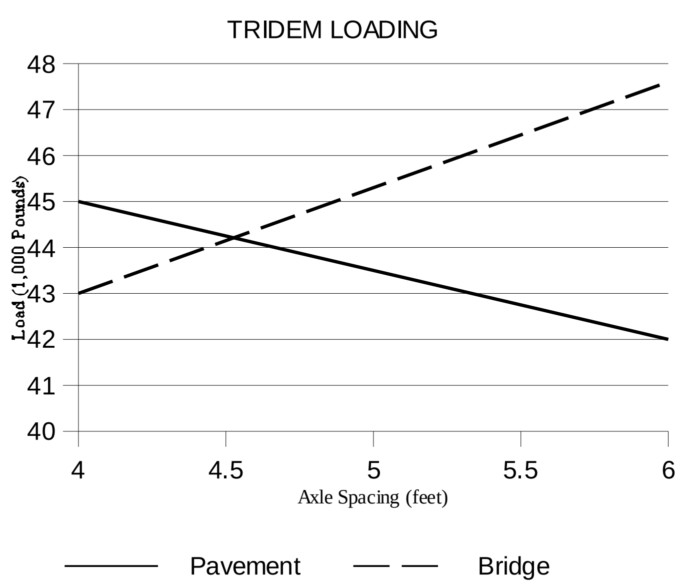
[27] An NPRM published April 14, 1997 (62 FR 18170) discusses a petition by Truck Trailer Manufacturer's Association to prohibit any device that is capable of dumping air individually from either of the two axle suspension systems on a semitrailer equipped with air-suspended "spread" or "split" tandems. If this is adopted, it could exacerbate tire "scrub" in turns and decrease stability.

A six-axle semitrailer combination is more effective in reducing pavement damage than a five-axle semitrailer combination with a split-tandem (two trailer axles spread apart), which is allowed under the current Federal bridge formula. Table VI-8 provides the weight limits for a tridem axle between four and eight feet and Figure VI-8 illustrates the impact on pavement and bridges.

**TABLE VI-8**
**TRIDEM AXLE WEIGHT LIMIT**

| Distance Between Adjacent Axles (feet) | Load at LEF=1 | Allowable Bridge Load (1,000 pounds) |
|---|---|---|
| 4 | 45 | 43 |
| 6 | 42 | 48.6 |
| 8 | 40 | ------ |

**FIGURE VI-8**
**PAVEMENT AND BRIDGE IMPACT OF TRIDEM AXLE**



## USE OF TRIDEMS

Tridem axles could be considered as a way to increase truck load capacity while reducing pavement damage.[28] There already has been a switch from three-axle to four-axle single unit trucks by many heavy bulk freight haulers, and as noted above, significant pavement cost savings may be possible. The 80,000-pound GVW limit poses a constraint on adding axles to five-axle combinations because, under the GVW limit, the extra axle would reduce the payload.

When viewed using the AASHTO load-equivalence factors, combinations with tridem axles generally have much lower pavement costs per ton of freight carried than conventional five-axle combinations. To illustrate this, as shown in Figure VI-9, a six-axle tractor-semitrailer loaded to 90,000 pounds with a rear tridem carrying 44,000 pounds produces 2.00 ESALs on flexible pavements and 3.83 ESALs on rigid pavements. The corresponding ESAL values for a conventional five-axle tractor-semitrailer carrying 80,000 pounds are 2.37 (flexible) and 3.94 (rigid). However, as noted earlier, the reduced pavement costs of the tridem axle require increasing the allowable gross vehicle weight, in part because of the increased tare weight of the tridem axle.

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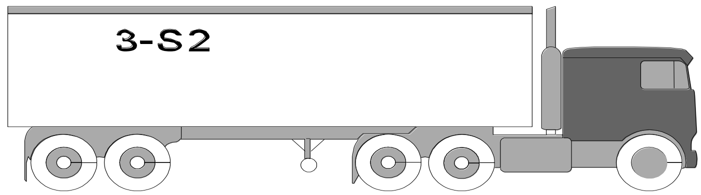
[28] Both the TRB *Special Report 225* and the AASHTO TS&W Subcommittee suggest consideration of the TTI bridge formula which could allow about 90,000 pounds for a six-axle tractor-semitrailer combination.

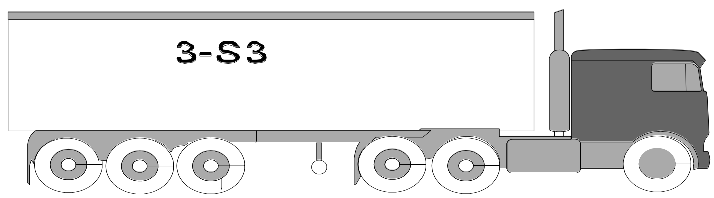
**FIGURE VI-9**
**ESAL COMPARISON OF 5-AXLE AND 6-AXLE COMBINATIONS ON PAVEMENT**

Five-Axle Tractor-Semitrailer




| | | | | Total |
|---|---|---|---|---|
| Weight (lbs) | 34,000 | 34,000 | 12,000 | 80,000 |
| ESALs | | | | |
| Flexible | 1.09 | 1.09 | 0.19 | 2.37 |
| Rigid | 1.88 | 1.88 | 0.18 | 3.94 |

Six-Axle Tractor-Semitrailer




| | | | | Total |
|---|---|---|---|---|
| Weight (lbs) | 44,000 | 34,000 | 12,000 | 90,000 |
| ESALs | | | | |
| Flexible | 0.72 | 1.09 | 0.19 | 2.00 |
| Rigid | 1.77 | 1.88 | 0.18 | 3.83 |

Assuming tare weights of 28,000 and 29,500 pounds for the five- and six-axle combinations, respectively, and using the AASHTO load equivalence factors, the ESALs per 100,000,000 pounds of payload for the trucks shown in Figure VI-9 are shown in Table VI-9. Research by others indicates a significantly smaller result in reduction of ESALs from increased payloads, for flexible pavements a reduction of 4 ESALs as opposed to 14 ESALs and for rigid pavements a reduction of 11 ESALs as opposed to 17 ESALs per million tons of payload.

**TABLE VI-9**
**ESALs PER 100,000,000 POUNDS OF PAYLOAD FOR 5- AND 6-AXLE COMBINATION**

| | Flexible Pavement | Rigid Pavement |
|---|---|---|
| 5-Axle Tractor-Semitrailer | 46 | 76 |
| 6-Axle Tractor Semitrailer | 33 | 63 |

# ROADWAY GEOMETRY IMPACTS

## ELEMENTS OF ROADWAY GEOMETRY IMPACTING TRUCK OPERATIONS

### INTERCHANGE RAMPS

Access and exit ramps for controlled access highways are intended to accommodate design vehicles at certain design speeds, as well as for high speed and low speed offtracking by combination vehicles. AASHTO policy recommends widening to accommodate combination vehicles. For example, the width of a one-lane ramp, with no provision for passing a stalled vehicle, would be 15 feet on a tangent section.

The extreme case for design consideration occurs when traffic is congested and stop-and-go conditions are present. The speed component to the offtracking equation is negligible and maximum offtracking to the inside of the curve occurs. Under this condition, the turnpike doubles analyzed in this study offtrack 20 percent more than a five-axle, 53-foot semitrailer combination and as a result encroach on adjacent lanes or shoulders and necessitate widening beyond AASHTO standards.

### INTERSECTIONS

Most trucks and truck combinations turning at intersections encroach on either the roadway shoulder or adjacent lanes. For example, the turning path of a truck making a right turn is generally controlled by the curb return radius, whereas the turning path in left turns is not constrained by roadway curbs, but may be constrained by median curbs and other traffic lanes. Combination vehicles with long semitrailers are critical in the determination of improvements to intersections required to accommodate offtracking requirements.

It is generally agreed that proper design and operation requires that no incursion into the path of vehicles traveling in opposing directions of flow be allowed. A higher standard is often used in design, especially in urban areas, where no incursion into any adjacent lane is allowed. This is particularly critical at signalized intersections where heavy traffic is a prevailing condition. A substantial number of intersections on the existing highway and street network cannot accommodate even a five-axle tractor semitrailer combination with a 48-foot semitrailer under the more stringent standard. Even more intersections would be inadequate to accommodate vehicles which offtrack more than the standard a 48-foot semitrailer.

Currently there are a substantial number of intersections on the highway and street network where improvements for combinations with semitrailers over 48 feet are not feasible and controls on vehicles, routing or travel times are required. Examples of common constraints to intersection improvements are bridges, buildings and sensitive environmental or historic plots. The use of permits in such cases can provide a desirable level of control, to the extent that they are enforced. Additionally, staging areas should be provided where routes and intersections have prohibitive constraints off the NN.

## CLIMBING LANES

The ability of a truck to maintain speed on a grade is described by the term “gradeability” and the ability of a truck to start on a grade from a standstill is termed “startability.” Truck “driveability” is defined as the percentage grade on which full throttle is required in top gear to maintain cruising speed. The ability of various trucks to start and to maintain speeds on grades is a complex subject which primarily depends on net engine horsepower, torque, gearing, drive train efficiency, friction, GVW and minimum allowable speed. Gradeability and startability are discussed more fully in Chapter 5, Safety and Traffic Operations. The AASHTO recommends that separate climbing lanes be provided on grades that have substantial truck traffic and that cause typical trucks to slow by more than 10 miles per hour.

## CROSS SECTION

Cross section refers to the shape of the surface of the roadway transverse to the direction of traffic[29]. Under normal operating conditions, cross section is not a dominant factor in increased TS&W, but under extreme icing conditions, a superelevated cross slope can be a significant problem for vehicles which have greater off-tracking. The presence of cross slope discontinuities can also be a problem for vehicles more prone to rollover because of the dynamic forces which they tend to introduce.

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[29] The major determinants of the cross section are the number of lanes, the presence of curbing or shoulders, and cross slope. Generally, a slight cross slope is designed into the cross section to assist in proper drainage of precipitation. Often this slope breaks to a steeper slope at the shoulder line, on a divided multilane highway the cross slope is generally highest at the centerline.

## HORIZONTAL CURVATURE

The rear wheels of trucks and truck combinations traversing horizontal curves generally offtrack to one side or the other of the paths of the wheels on the steering axle. When a truck is traveling at higher speeds the rear wheels can follow a path outside that of the steering wheels. This effect is relatively small and virtually never results in the need to make geometric improvements beyond those normally made in the design process. On the other hand, when offtracking is to the inside of the curve at lower speeds and in stop-and-go traffic, it is usually more substantial and must be accommodated. Trucks in combination with longer trailers are often prone to producing relatively large amounts of offtracking beyond that provided for in AASHTO standards. On roadways not constructed to AASHTO standards more improvement would be required to accommodate longer combinations where offtracking would exceed normal lane width.

## VERTICAL CURVE LENGTH

The height of the truck driver's eye is a distinct advantage of trucks over passenger vehicles for crest vertical curves which are designed to maximize stopping sight distance. Vertical curves are generally designed for passenger cars as the passenger car driver's eye is closer to the pavement than that of the truck driver. For a sag vertical curve going from a downgrade to an upgrade, headlight coverage and passenger comfort usually control. The vehicles considered in this study have braking distances similar to vehicles in common use at this time; therefore no geometric adjustments would be required.

## SIGHT DISTANCES- STOPPING AND PASSING

Passing distances involving trucks can be significantly longer than when no trucks are present. Longer trucks increase the distance required for a car or truck to pass and require more care in order do so safely.

Drivers of passenger cars passing trucks, and drivers of trucks who desire to pass other vehicles, are expected to follow the rules of the road and exercise discretion, passing only where sight distance is adequate. On multi-lane highways passing is generally not as critical as passing on a two-lane highway with traffic in opposing directions. Sight distance criteria for marking passing and no-passing zones on two-lane highways are more appropriate for a passenger car passing another passenger car, and do not consider trucks, even the standard truck and 48-foot semitrailer combination vehicle at 80,000 pounds.

Increasing TS&W limits for LCVs could require as much as 8 percent more passing sight distance for cars passing LCVs on two-lane roads and longer and/or heavier trucks would require incrementally longer passing sight distances to safely pass cars on two-lane roads.

## DIMENSIONAL LIMITS IMPACTING TRUCK MANEUVERS

### LENGTH LIMITS OF SEMITRAILERS

The Surface Transportation Assistance Act (STAA) of 1982 established a minimum length limit that requires States to allow the operation of a semitrailer of at least 48 feet on the National Network (NN) for large trucks. All States now allow up to 53 feet on at least some highways. The majority of States prohibit semitrailers longer than 53 feet, the exceptions being Alabama, Arizona, Arkansas, Colorado, Kansas, Louisiana, New Mexico, Oklahoma, Texas, and Wyoming.[30] These States allow trailers in the 57- to 60-foot range to operate.

### LENGTH LIMITS FOR DOUBLE-TRAILERS IN COMBINATION

The STAA of 1982 also established a requirement for States to allow, at a minimum, the operation of two 28-foot trailers (twins) in combination on the Interstate and NN. About one-fourth of the States prescribe 28 feet as a maximum; the others allow additional length up to 30 feet with 28.5 feet being the most common.

Prior to the Intermodal Surface Transportation Efficiency Act of 1991, Federal law allowed States to permit longer trailers in combination, commonly referred to as doubles, but did not require States to allow them.

### OVERALL LENGTH LIMITS

The STAA of 1982 established a prohibition against State laws that specify a maximum length for tractor-semitrailer and STAA[31] double combinations operating on the Interstate and NN. Consequently, most States control total length on the NN by limiting semitrailer and trailer lengths. About two thirds of the States have some form of control of total combination length for non-NN highways. While there are no proposals that the Federal law prescribe a total length limit at this time, offtracking standards could effectively limit overall lengths for single- and double-trailer combinations.

### VEHICLE WIDTH AND HEIGHT LIMITS

Vehicle widths and heights, although important from the standpoint of safety and traffic operations, have little effect on roadway geometric design except for lane width.

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[30] *Federal Size Regulations for Commercial Motor Vehicles,* U.S. DOT, Publication No. FHWA-MC-96-03.

[31] Also known as Western doubles

## ROADWAY GEOMETRY AND TRUCK OPERATING CHARACTERISTICS

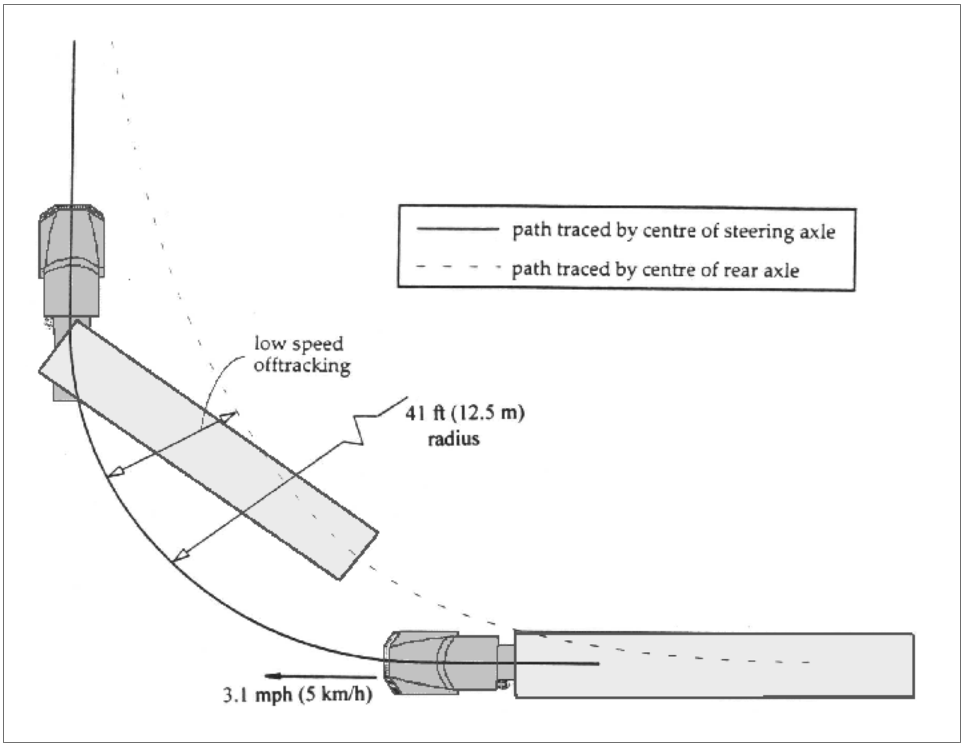
When a vehicle makes a turn, its rear wheels do not follow the same path as its front wheels. The magnitude of this difference in path, known as "offtracking", generally increases with the spacing between the axles of the vehicle and decreases for larger radius turns. Offtracking of passenger cars is minimal because of their relatively short wheel bases; however, many trucks offtrack substantially. The magnitude of the offtracking is often measured by the differences in the paths of the centerlines of the front and subsequent axles.

### OFF-TRACKING AND INTERSECTION MANEUVERS

#### *Low-Speed Off-Tracking*

When a combination vehicle makes a low-speed turn--for example a 90 degree turn at an intersection--the wheels of the rearmost trailer axle follows a path several feet inside the path of the tractor steering axle. This is called low-speed offtracking. Excessive low-speed offtracking may make it necessary for the driver to swing wide into adjacent lanes to execute the turn (that is, to avoid climbing inside curbs or striking curbside fixed objects or other vehicles). When negotiating exit ramps, excessive offtracking can result in the truck tracking inboard onto the shoulder or up over inside curbs. This performance attribute is affected primarily by the distance from the tractor kingpin to the center of the trailer rear axle, or the wheelbase of the semitrailer. In the case of multiple-trailer combinations, the effective wheelbase(s) of all the trailers in the combination, along with the tracking characteristics of the converter dollies, dictate this property. In general, longer wheelbases worsen low-speed offtracking. Figure VI-10 illustrates low-speed off-tracking in a 90-degree turn for a tractor-semitrailer.

**FIGURE VI-10**
**LOW-SPEED OFF-TRACKING**

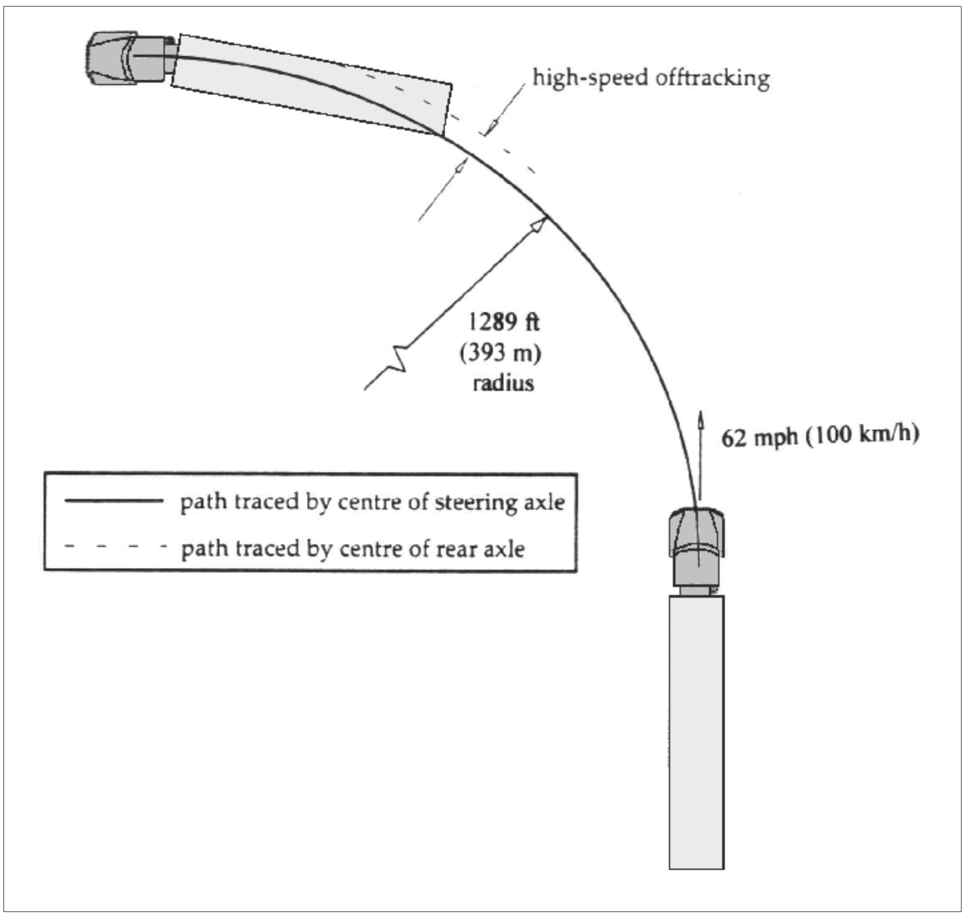



The standard double-trailer combination (two 28-foot trailers) and triple combinations (three 28-foot trailers) exhibit better low speed offtracking performance when compared to a standard tractor and 53-foot semitrailer combination. This is because they have more articulation points in the vehicle combination, and use trailers with shorter wheelbases.

### *High-Speed Off-Tracking*

High-speed offtracking, on the other hand, is a dynamic, speed-dependent phenomenon. It results from the tendency of the rear of the truck to move outward due to the lateral acceleration of the vehicle as it makes a turn at higher speeds. High-speed offtracking is actually the algebraic combination of the low-speed offtracking toward the inside of the turn and the outward displacement due to the lateral acceleration.  As the speed of the truck increases, the total offtracking decreases until, at some particular speed, the rear trailer axles follow exactly the tractor steering axle.  At still higher speeds, the rear trailer axles will track outside of the tractor steering axle.  The speed-dependent component of offtracking is primarily a function of the spacing between truck axles, the speed of the truck, and the radius of the turn; it is also dependent on the loads carried by the truck axles and the truck suspension characteristics. Figure VI-11 illustrates off-tracking maneuver for a standard tractor-semitrailer.

**FIGURE VI-11**
**HIGH-SPEED OFF-TRACKING**



## OFF-TRACKING ON MAINLINE HORIZONTAL CURVES AND INTERCHANGE RAMPS

An analysis of offtracking and swept path width for horizontal curves designed in accordance with AASHTO's high-speed design criteria (1994) was completed for the vehicle configurations considered in this study. Such curves are typically found on mainline roadways and higher speed ramps. Alternative design criteria that permit higher unbalanced lateral acceleration and, thus, tighter radii can be used under AASHTO policies for horizontal curves with design speeds of 40 mph or less, which are typically found on ramps and turning roadways at intersections.

Under AASHTO policy, the minimum radius for a horizontal curve varies with the roadway design speed and the maximum super-elevation rate.[32] For horizontal curves with a maximum super-elevation rate of 0.06 ft/ft (the maximum super-elevation rate most commonly used by State highway agencies), the minimum radii permitted by the AASHTO high-speed design criteria vary with design speed, as shown in Table VI-10.

**TABLE VI-10**
**AASHTO HIGH-SPEED DESIGN CRITERIA**

| Design Speed (MPH) | Minimum Radius (feet) |
|---|---|
| 30 | 273 |
| 40 | 509 |
| 50 | 849 |
| 60 | 1,348 |
| 70 | 2,083 |

AASHTO policy for horizontal curve design specifies pavement widening on sharp radius horizontal curves for which truck offtracking is a concern. For the minimum-radius curves listed above on a highway with a lane width of 12 feet on tangent sections, only the 273-foot radius curve (for a 30-mph design speed) would require widening. AASHTO criteria call for such a curve to be widened from 12 to 14.5 feet.

An analysis was conducted to determine whether minimum-radius curves with the widths described above, designed in accordance with AASHTO policies, would be capable of accommodating each of the vehicle configurations considered in this study. This analysis was conducted by comparing the lane or ramp width to the swept path width of the truck making a turn with the specified radius. Tables VI-11 and VI-12 present this comparison for selected truck configurations.

32 AASHTO, 1994.

The swept path widths in Table VI-11 are based on fully-developed offtracking determined with the Glauz and Harwood model for a truck traversing the curve with a travel speed equal to the roadway design speed. None of the swept path widths shown in Table VI-11 exceed the corresponding lane width for mainline roadways or the corresponding ramp widths, although the turnpike double with 53-foot trailers does require nearly all of the (widened) 14.5 feet of the 30-mph AASHTO horizontal curve. Thus, there is no indication that any of the Study vehicles, traveling at the roadway design speed, would necessarily offtrack into an adjacent lane or shoulder of the roadway or ramps designed in accordance with AASHTO policies.

Table VI-12 presents comparable results when the trucks travel at very slow speeds on these same curves, such as they may be required to do in congested traffic. The swept path widths at low speed in Table VI-12 are generally greater than those in Table VI-11, but except for the Turnpike Doubles, none of the study vehicles would encroach on adjacent lanes or shoulders. Both Turnpike Doubles would encroach on adjacent lanes or shoulders on 30-mph design speed horizontal curves, and the Turnpike Double with 53-ft trailers would low-speed off-track into adjacent lanes or shoulders on 40-mph design speed horizontal curves and on 30-mph design speed ramps.

## TABLE VI-11
## SWEPT PATH WIDTH FOR SELECTED TRUCKS ON HORIZONTAL CURVES AT AASHTO DESIGN SPEED CRITERIA

| | | Maximum Swept Path Width (feet) at the Design Speed on the Sharpest Horizontal Curve Allowed by AASHTO Design Policy | | |
|---|---|---|---|---|
| | **Design Speed (mph)** | 30 | 40 | 60 |
| | **Curve Radius (feet)** | 273 | 509 | 1,348 |
| **Truck Configuration** | **Length (feet)** | | | |
| **Three-Axle Single Unit Truck** | 39.5 | 8.12 | 8.00 | 8.00 |
| **Five-Axle Tractor Semitrailer** | 64.3 | 10.09 | 8.56 | 8.50 |
| **Five-Axle Tractor Semitrailer** | 76.8 | 11.88 | 9.43 | 8.50 |
| **Six-Axle Tractor Semitrailer** | 64.3 | 10.05 | 8.63 | 8.50 |
| **Six-Axle Tractor Semitrailer** | 76.8 | 11.79 | 9.48 | 8.50 |
| **Five-Axle Truck-Full Trailer** | 63.3 | 8.32 | 8.00 | 8.00 |
| **Seven-Axle Truck-Full Trailer** | 61.3 | 8.44 | 8.00 | 8.00 |
| **Six-Axle Western Double** | 74.3 | 9.02 | 8.50 | 8.50 |
| **Seven-Axle Rocky Mtn Double** | 99.3 | 11.62 | 9.21 | 8.50 |
| **Eight-Axle B-Train Double** | 84.3 | 10.39 | 8.70 | 8.50 |
| **Nine-Axle Turnpike Double** | 114.3 | 12.85 | 9.83 | 8.50 |
| **Nine-Axle Turnpike Double** | 124.3 | 14.29 | 10.54 | 8.50 |
| **Seven-Axle Triple** | 109.0 | 9.69 | 8.50 | 8.50 |

**TABLE VI-12**
**SWEPT PATH WIDTH FOR SELECTED TRUCKS ON HORIZONTAL CURVES**
**AT VERY LOW SPEED**

| | | Maximum Swept Path Width (feet) at Very Low Speed on the Sharpest Horizontal Curve Allowed by AASHTO Design Policy | | |
|---|---|---|---|---|
| | Design Speed (mph) | 30 | 40 | 60 |
| | Curve Radius (feet) | 273 | 509 | 1,348 |
| Truck Configuration | Length (feet) | | | |
| Three-Axle Single Unit Truck | 39.5 | 8.80 | 8.26 | 8.00 |
| Five-Axle Tractor Semitrailer | 64.3 | 11.54 | 9.95 | 8.80 |
| Five-Axle Tractor Semitrailer | 76.8 | 13.65 | 11.12 | 9.30 |
| Six-Axle Tractor Semitrailer | 64.3 | 11.21 | 9.74 | 8.67 |
| Six-Axle Tractor Semitrailer | 76.8 | 13.22 | 10.85 | 9.14 |
| Five-Axle Truck-Full Trailer | 63.3 | 9.02 | 8.38 | 8.00 |
| Seven-Axle Truck-Full Trailer | 61.3 | 8.98 | 8.34 | 8.00 |
| Six-Axle Western Double | 74.3 | 10.38 | 9.31 | 8.55 |
| Seven-Axle Rocky Mtn Double | 99.3 | 13.65 | 11.15 | 9.35 |
| Eight-Axle B-Train Double | 84.3 | 11.92 | 10.16 | 8.89 |
| Nine-Axle Turnpike Double | 114.3 | 15.04 | 11.92 | 9.67 |
| Nine-Axle Turnpike Double | 124.3 | 16.69 | 12.83 | 10.05 |
| Seven-Axle Triple | 109.0 | 12.15 | 10.40 | 9.14 |

## INTERSECTION MANEUVERS

Trucks turning at intersections have the potential to encroach on either the roadway shoulder or adjacent lanes. The turning path of a truck making a right turn is controlled by the curb return radius. Truck paths in left turns are not constrained by roadway curbs, but may be constrained by median curbs and other traffic lanes.

The analyses assume that the turn is made at the intersection of two two-lane or two four-lane streets and that the truck making the turn positions itself as far to the left as possible on the approach to the intersection without encroaching on the opposing lanes, and completes the turn as far to the left as possible without encroaching on the opposing lanes. In other words, the truck does encroach on adjacent lanes for traffic moving in the same direction (on four-lane roads), but does not encroach on lanes used by traffic moving in the opposing direction. The maneuver specified above requires a turning radius for the truck tractor which is 8 feet longer than the curb return radius on a two-lane road, and 20 feet longer than the curb return radius on a four-lane road, if all lanes are 12 feet wide.

Table VI-13 presents estimates of encroachment on the curb return for selected trucks for right turns at corners with curb return radii of 30, 60, and 100 feet. The data in these tables are based on the maximum value of the partially-developed offtracking because, in most cases, offtracking will not develop fully as a large truck proceeds through an intersection turning maneuver.

**TABLE VI-13**
**CURB ENCROACHMENT FOR 90-DEGREE RIGHT-TURN MANEUVERS AT INTERSECTION OF FOUR-LANE ROADS**

| | | Encroachment on Curb Return | | |
|---|---|---|---|---|
| **Truck Configuration** | **Length (feet)** | **30-foot Curb Return Radius** | **60-foot Curb Return Radius** | **100-foot Curb Return Radius** |
| **Three-Axle Single Unit Truck** | 39.5 | -9.97 | -12.07 | -13.37 |
| **Five-Axle Tractor Semitrailer** | 64.3 | -0.09 | -4.47 | -7.88 |
| **Five-Axle Tractor Semitrailer** | 76.8 | 6.42 | 1.11 | -3.49 |
| **Six-Axle Tractor Semitrailer** | 64.3 | -1.06 | -5.27 | -8.49 |
| **Six-Axle Tractor Semitrailer** | 76.8 | 5.34 | 0.16 | -4.25 |
| **Five-Axle Truck-Full Trailer** | 63.3 | -7.41 | -10.29 | -12.17 |
| **Seven-Axle Truck-Full Trailer** | 61.3 | -8.10 | -10.82 | -12.54 |
| **Six-Axle Western Double** | 74.3 | -4.06 | -8.01 | -10.37 |
| **Seven-Axle Rocky Mt. Double** | 99.3 | 6.73 | 1.23 | -3.48 |
| **Eight-Axle B-Train Double** | 84.3 | 1.58 | -3.23 | -7.02 |
| **Nine-Axle Turnpike Double** | 114.3 | 11.02 | 4.91 | -.057 |
| **Nine-Axle Turnpike Double** | 124.3 | 15.38 | 8.83 | 2.69 |
| Seven-Axle Triple | 109.0 | 1.97 | -2.97 | -6.87 |

The encroachment columns in Table VI-13 indicates the amount of encroachment on the curbline by the rear axles of the turning truck. a negative value for encroachment indicates that the truck does not encroach on the curbline. a positive value indicates that encroachment does occur and the magnitude of the value indicates the maximum encroachment distance. Where a positive value is shown for the encroachment distance, that particular truck could make the turn without encroaching on the curbline only if it encroached on an opposing lane(s) instead.

The turn from a four-lane street to another four-lane street was chosen as the case of interest because none of the trucks considered—baseline or study vehicles—are capable of making a short-radius turn from one two-lane street to another without encroaching on either the curbline or an opposing lane, unless the curb return radius is very large (100 feet, say), and then only by selected very short trucks.

With a 30-foot curb return radius (Table VI-13), many of the truck configurations will encroach on the curb return, with a few exceptions. The single unit trucks, the tractors with a 45-foot semitrailer, the truck-full trailers, and the western twins can successfully negotiate these turns. The encroachment of the five-axle semitrailer configuration with a 45-foot trailer is very marginal, however, as is the triple with 28-foot trailers.

By expanding the curb return radius to 60 feet (Table VI-13), nearly all configurations examined can negotiate the turn without encroaching on the curb return. The exceptions which can not successfully complete the turn are the tractors with 57.5-foot semitrailers, the longer Rocky Mountain double, and (particularly) the turnpike doubles.

At an even larger curb return radius of 100 feet (Table VI-13), all but the turnpike double with 53-foot trailers can properly negotiate the turn.

## CURRENT REGULATIONS ON OFF-TRACKING

Federal law is silent on offtracking-related characteristics of trucks and combinations. In particular, it specifies no requirements on kingpin setting, kingpin setback, and rear overhang. In nearly one-half of the States regulations require a kingpin setting for semitrailers over 48 feet in length. Although there is no one uniform standard, the most common setting distance is 41 feet.

## REGULATION ALTERNATIVES

Control of offtracking can be accomplished in one of two ways. The first requires considering the length limit(s) of the semitrailer(s) within the context of total combination length limit, restrictions on the kingpin setback, wheelbase, and effective rear overhang as in the Canadian regulations. a more straightforward alternative is a performance specification requiring that a truck be able to turn through a given angle, at a given speed, within a defined swept path as in the European regulations.